NASA TECHNICAL MEMORANDUM

NASA TM X-53375

December 29, 1965

NASA TM X-53375

VELOCITY REQUIREMENTS FOR THE EARTH RETURN PHASE OF PLANETARY MISSIONS

By Robert M. Jones and William T. Stephens
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ABSTRACT

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Results are presented graphically in parametric form, showing characteristic velocity and burning time as a function of approach hyperbolic excess velocity, maximum allowable entry velocity, thrust-to-weight ratio, specific impulse and entry flight path angle. The allowable earth entry velocity ranges from local parabolic to 18 km/sec.

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PROPULSION AND VEHICLE ENGINEERING LABORATORY
RESEARCH AND DEVELOPMENT OPERATIONS

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LIST OF SYMBOLS

Symbol	Definition
F	Thrust
F/W_o	Thrust-to-weight ratio
g	Acceleration of gravity for a mean spherical, rotating Earth = 9.80655 m/sec^2
g_n	Mean apparent gravity at sea level; international standard for weight-mass conversion; 9.81992 m/sec^2
I_{sp}	Specific Impulse
m	Mass
r	Radius from center of the Earth to vehicle
r_o	Radius to vehicle at initial conditions
r_E	Radius to vehicle at reentry conditions
$r_\oplus$	Radius of mean spherical Earth
t_b	Burning time of engine
V	Inertial velocity
V_e	Reentry velocity
ΔV_c	Characteristic velocity
$\Delta(\Delta V_c)$	Change in characteristic velocity
V_∞	Hyperbolic excess velocity
V_∞(EMOS)	Hyperbolic excess velocity normalized to Earth's mean orbital speed $\left(\frac{V_\infty}{EMOS}\right)$

Symbol	Definition
W_o	Initial weight prior to reentry
W_p	Propellant weight
x	Range
β	Thrust vector orientation angle measured from the velocity vector to the thrust vector (positive clockwise)
θ	Flight path angle, measured from the local vertical (positive clockwise)
θ_E	Reentry angle, measured from the local vertical to the velocity vector (positive clockwise, $\theta_E = \theta - 180°$)
ψ	Central angle measured from local radius vector at ignition
ζ	Propellant ratio, $\frac{W_p}{W_o}$
$\mu_\oplus$	Gravitational constant of the Earth

Subscripts	Definition
o	Initial
$\oplus$	Earth
e	Reentry
ref	Reference conditions
r	The arbitrary altitude for which velocity, thrust-to-weight ratio, etc., are calculated

LIST OF SYMBOLS - Concluded

Abbreviations	Definition
deg	Degrees
km	Kilometers
m	Meters
lb	Pounds
s or sec	Seconds

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SUMMARY

Retro characteristic velocity requirements have been calculated for the earth return phase of planetary missions with maximum allowable earth entry velocities. The effects of key independent performance parameters on the characteristic velocity and associated burning time requirements have been investigated for the retro maneuver. The propulsion systems considered were low-energy chemical, high-energy chemical, and solid-core nuclear.

Results are presented graphically in parametric form, showing characteristic velocity and burning time as a function of approach hyperbolic excess velocity, maximum allowable entry velocity, thrust-to-weight ratio, specific impulse and entry flight path angle. The allowable earth entry velocity ranges from local parabolic to 18 km/sec.

SECTION I. INTRODUCTION

Preliminary mission analysis and vehicle design usually require a comprehensive knowledge of key performance parameters, particularly the mission characteristic velocity requirements. Furthermore, in view of the iterative processes of preliminary design and feasibility studies, it is desirable to have performance data in a parametric format with a wide variation of the key independent performance parameters.

Parametric data of this type have been presented for various phases of planetary missions in References 1 through 4. References 2, 3 and 4 present data for the earth departure, planet arrival and planet departure phases of typical Mars and Venus stopover missions.

However, data for the final phase of such missions, the earth return maneuver, are not included in these references.

Extensive studies have been made of the atmospheric flight portion of the earth return trajectory for planetary-class missions. Little data are available, however, for the retro-brake maneuver which may be required prior to atmospheric entry. This is the case when there is a limited entry speed the entry body can tolerate due to heat, g-loading or guidance restrictions. For example, unbraked earth reentry speeds of 16 km/sec (65,617 ft/sec) are not uncommon for Mars stopover missions. On the other hand, current estimates for allowable entry speeds, based on advanced technology, range from parabolic velocity (about 11 km/sec) to as high as 22 km/sec, an uncertainty factor of two. Until a higher degree of confidence is achieved for the high entry speeds, the mission planner must consider the possibility of having a retro during the earth return phase.

It is the purpose of this report to present parametric data illustrating the variation of characteristic velocity and the associated burning times for propulsive braking to various earth entry speeds from a wide range of approach hyperbolic excess velocities. Data are presented for a range of specific impulse values which typify storable chemical, high-energy chemical and solid-core nuclear propulsion systems. Single-stage braking is assumed in all cases. All calculations were made on an IBM 7090 computer using a Runge-Kutta numerical integration technique.

SECTION II. ASSUMPTIONS

The principal assumptions related to the analysis discussed and the results presented in this report are as follows:

(1) Deceleration via a single stage from an interplanetary transfer trajectory to specified end conditions.

(2) Tangential thrust

(3) Burnout altitude - 185 km

(4) Range of independent performance parameters:

V_∞ = 0.1 - 0.6 EMOS

F/W_o = 0.05 - 1.0

Storable propellant I_{sp} = 320 - 340 sec

High-energy chemical I_{sp} = 420 - 440 sec

Solid-core nuclear I_{sp} = 775 - 825 sec

$\theta_E = 60° - 90°$

$(V_e)_{max}$ = 11.03 - 18.0 km/sec

(5) Mean spherical earth model with

$\mu_\oplus = 398{,}613 \ km^3/sec^2$

$\gamma_\oplus = 6371.1$ km

(6) Earth mean orbital speed (EMOS) = 29,770 m/sec

SECTION III. ANALYSIS

The method employed in this analysis is based on the terminology and general equations of motion outlined in Reference 1. Referring to the following sketch, the general equations of motion for a point mass moving in planar motion under the influence of a central gravitational potential are as follows:

$$\dot{V} = \frac{F \cos \beta}{m} - g \cos \theta \tag{1}$$

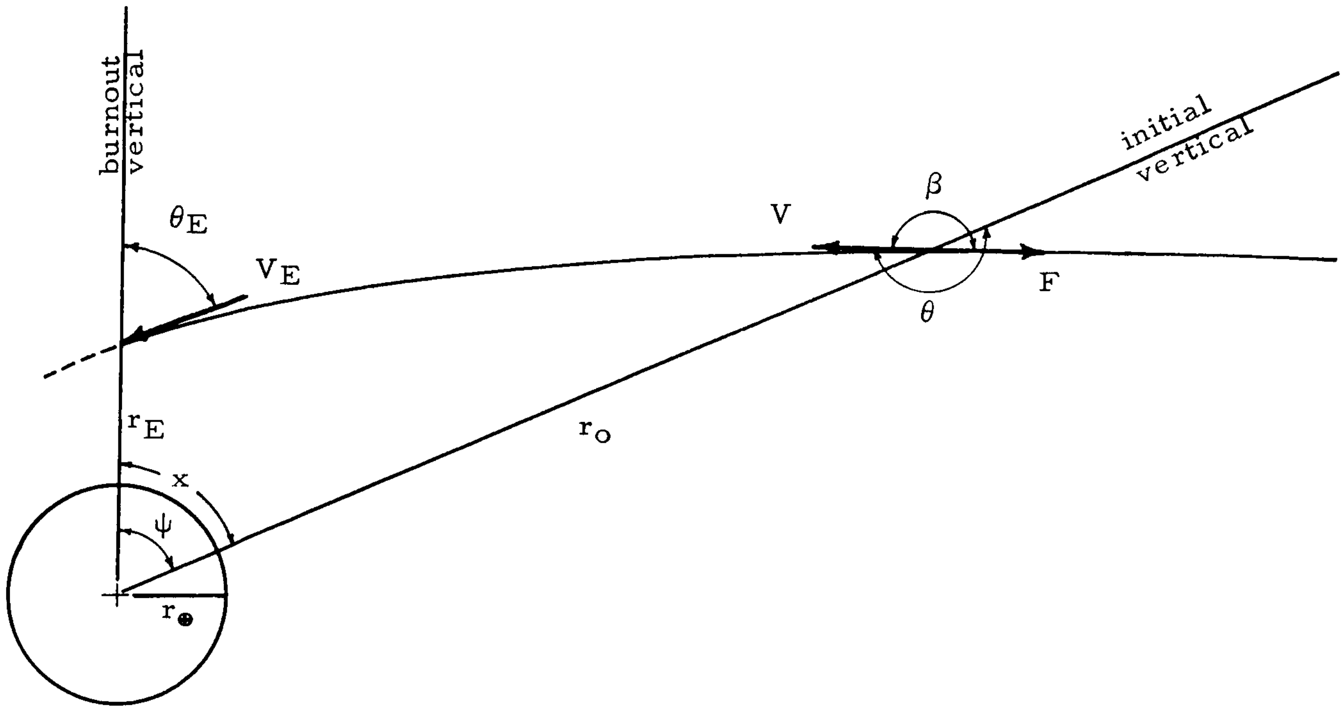
$$\dot{\theta} = \frac{F \sin \beta}{mV} + \left(\frac{g}{V} - \frac{V}{r}\right) \sin \theta \tag{2}$$

where

$$m = m_o + \int \dot{m} \, dt$$

and

$$\dot{m} = -F/V_{ex}$$



For tangential thrust braking, β = 180°, the above equations reduce to

$$\dot{V} = -\frac{F}{m} - g \cos \theta \tag{3}$$

$$\dot{\theta} = \left(\frac{g}{V} - \frac{V}{r}\right) \sin \theta \tag{4}$$

Numerical integration of equations 3 and 4 determines the velocity and flight path angle. Thus,

$$V = \int \dot{V}\, dt \tag{5}$$

$$\theta = \int \dot{\theta}\, dt \tag{6}$$

Range and altitude are then calculated by the relations

$$X = \int \frac{r_\oplus}{r} V \sin \theta\, dt \tag{7}$$

$$r = r_o + \int V \cos \theta\, dt \tag{8}$$

With burning time having been determined during the numerical integration of the equations of motion, the propellant ratio for constant thrust and specific impulse can be calculated from the relationship

$$\zeta = \left(\frac{F}{W_o}\right)\frac{t_b}{I_{sp}} \tag{9}$$

Once ζ is determined the main parameter of interest in the present study, the stage characteristic velocity, can be found from

$$\Delta V_c = g_n I_{sp} \ln \frac{1}{1-\zeta} \tag{10}$$

where characteristic velocity represents the energy actually expended by the stage in braking from the approach velocity to the desired entry velocity, taking into account "gravity losses" which, in the case of braking, represent the undesirable acceleration caused by the gravitational attraction.

The velocity at initiation of braking (t = o) is given by the equation

$$V_o = \sqrt{(V_\infty)^2 + (V_{esc})^2_{r = r_o}} \tag{11}$$

where V_{esc} is the local parabolic escape velocity and V_∞ is the hyperbolic excess velocity associated with the approach trajectory.

Burnout or reentry conditions, for the case of a braking maneuver, are preset, and the initial conditions, which result in the desired end values, must be determined for each combination of the independent performance parameters. Thus, the calculation of the braking trajectory and velocity requirements is a "reverse integration" problem. Initially, the reentry altitude, r_E, and the flight path angle, θ_E, were fixed and the entry velocity, V_e, varied from local parabolic up to 18 km/sec. Then, with r_E remaining fixed, θ_E was allowed to vary from 60° - 90° over the full range of V_e.

SECTION IV. DISCUSSION OF RESULTS

Before proceeding into the discussion of results, it is of interest to note the variation of entry velocity at the assumed burnout altitude of 185 km if no propulsive braking is employed. This variation is shown as a function of V_∞ in Figure 1 with V_e being calculated from

$$V_e = \sqrt{(V_\infty)^2 + (V_{esc})^2_{r = r_E}}$$

which is similar to equation 11 but with V_{esc} being calculated at 185 km. This curve is shown for reference and to illustrate that, depending upon the approach V_∞ and the allowable V_e, there may or may not be a retro maneuver required. This explains why, in some later figures, the characteristic velocity requirements go to zero at a relatively high value of V_∞. For example, Figure 1 indicates that if the allowable entry speed at 185 km were 20 km/sec there would be no retro required for values of V_∞ below 0.56 EMOS (V_∞ is commonly expressed as a fraction of the earth's mean orbital speed, EMOS, but must be in km/sec for equation 11). Previous studies indicate that the V_∞ at earth return from realistic Mars and Venus flyby and stopover missions does not often exceed 0.5 EMOS, or an unbraked entry velocity of just over 18 km/sec. Consequently, a V_e of 18 km/sec was the maximum considered.

Figures 2a through 2d show parametrically the characteristic velocity requirements for retro to allowable entry velocities at 185 km of 11.03 (local parabolic escape), 12, 14, 16, and 18 km/sec for a specific impulse of 320 seconds. Similar data are shown in Figures 3a through 3d and in Figures 4a through 4d for specific impulses of 330 and 340 seconds, respectively, completing the assumed range of specific impulse for storable propellant retro systems. Analogous data for the high-energy chemical systems is presented in Figures 5 through 7, followed by data for nuclear systems in Figures 8 through 10.

All of the data presented in Figures 2 through 10 are for the nominal flight path angle of 90°. Figures 11 through 22 illustrate the increase in characteristic velocity for non-reference flight path angles. The characteristic velocity for a non-reference entry flight path angle is found by adding the associated penalty to the ΔV_c for $\theta = 90°$, i.e.,

$$(\Delta V_c)_\theta = (\Delta V_c)_{\theta = 90°} + \Delta\ (\Delta V_c)_\theta \tag{12}$$

Burning time requirements for the various combinations of I_{sp} and $(V_e)_{max}$ are shown parametrically in Figures 23 through 25 for the reference entry conditions. Burning times for non-reference flight path angles can be calculated from the relationship

$$(t_b)_\theta = (t_b)_{\theta = 90°} + \Delta t_b \tag{13}$$

where $(t_b)_{\theta = 90°}$ is read directly from the graphs and Δt_b is calculated from

$$\Delta t_b = \frac{I_{sp}}{F/W_o} \left[1 - e^{\frac{-\Delta(\Delta V_c)}{g_n\ I_{sp}}} \right] \tag{14}$$

In the above equation, $\Delta(\Delta V_c)$ is also read directly from the appropriate graph for the particular non-reference value of θ.

SECTION V. CONCLUSIONS

Use of the parametric data presented in this report provides the mission planner with sufficient information to make quick preliminary estimates of the stage design required for the earth return phase of various mission profiles. The data are comprehensive enough to allow quick sensitivity studies to determine the effect of such key performance parameters as maximum allowable entry velocity and entry flight path angle upon the preliminary design of the retro stage.

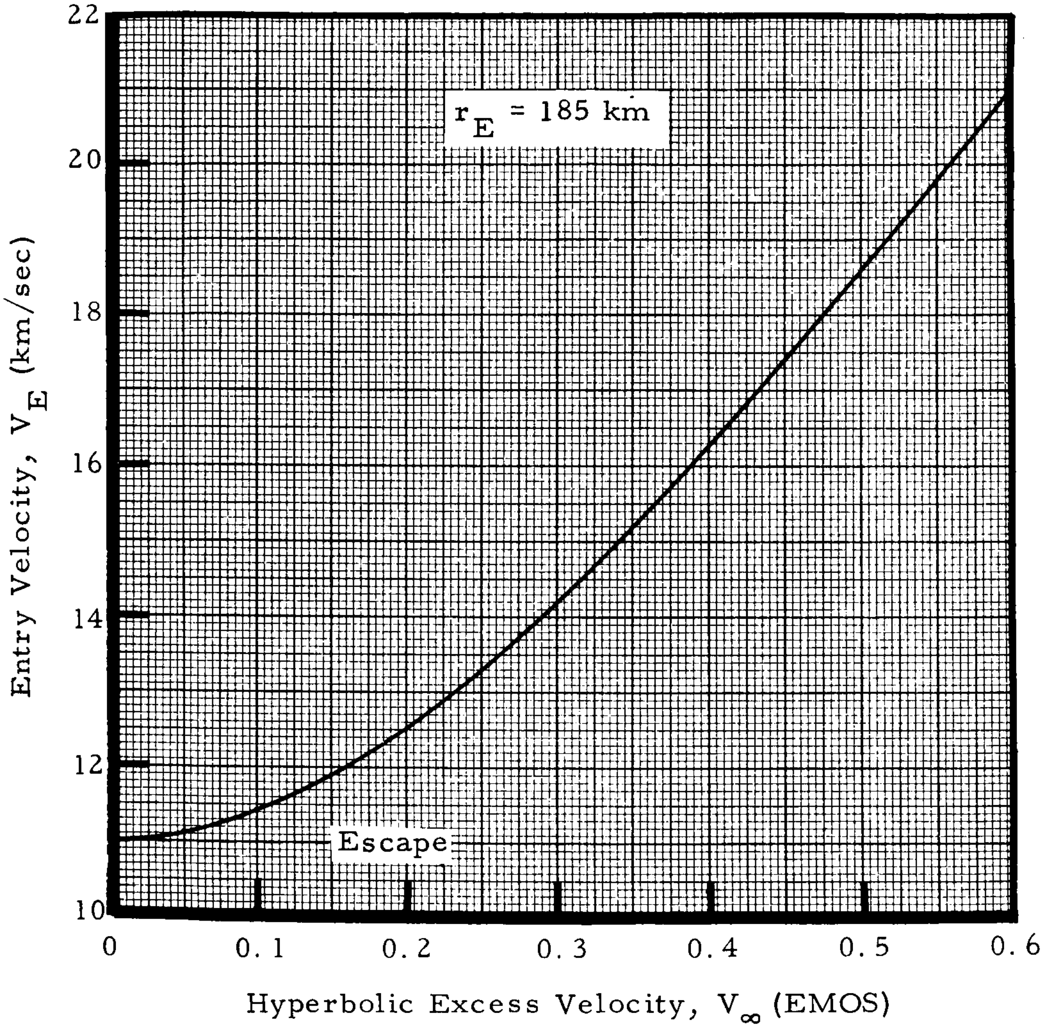


FIGURE 1. VARIATION OF ENTRY VELOCITY WITH HYPERBOLIC EXCESS VELOCITY

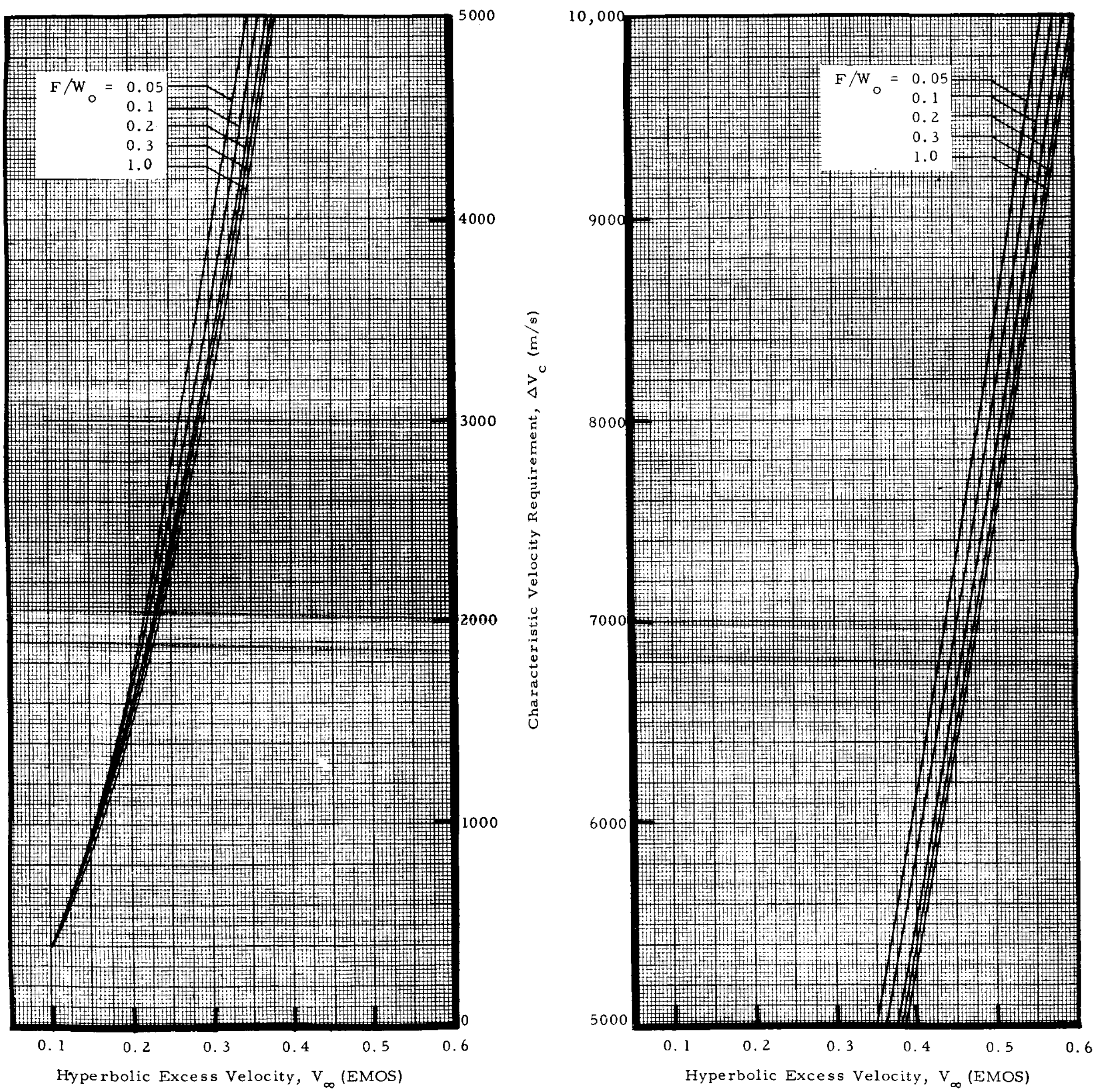


FIGURE 2a. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 320 s
$(V_e)_{max}$ = 11030 m/s

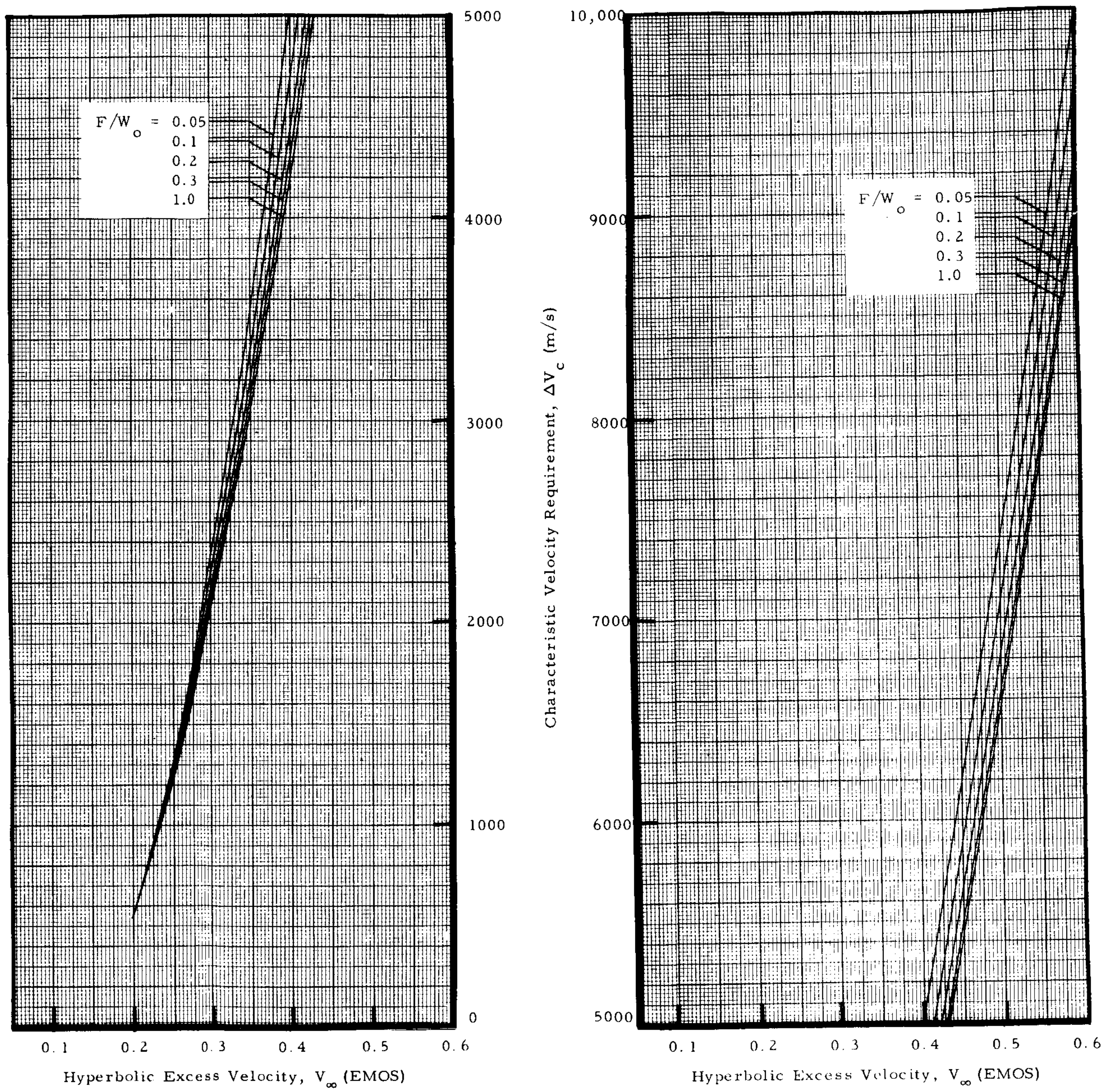


FIGURE 2b. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 320 s $(V_e)_{max}$ = 12000 m/s

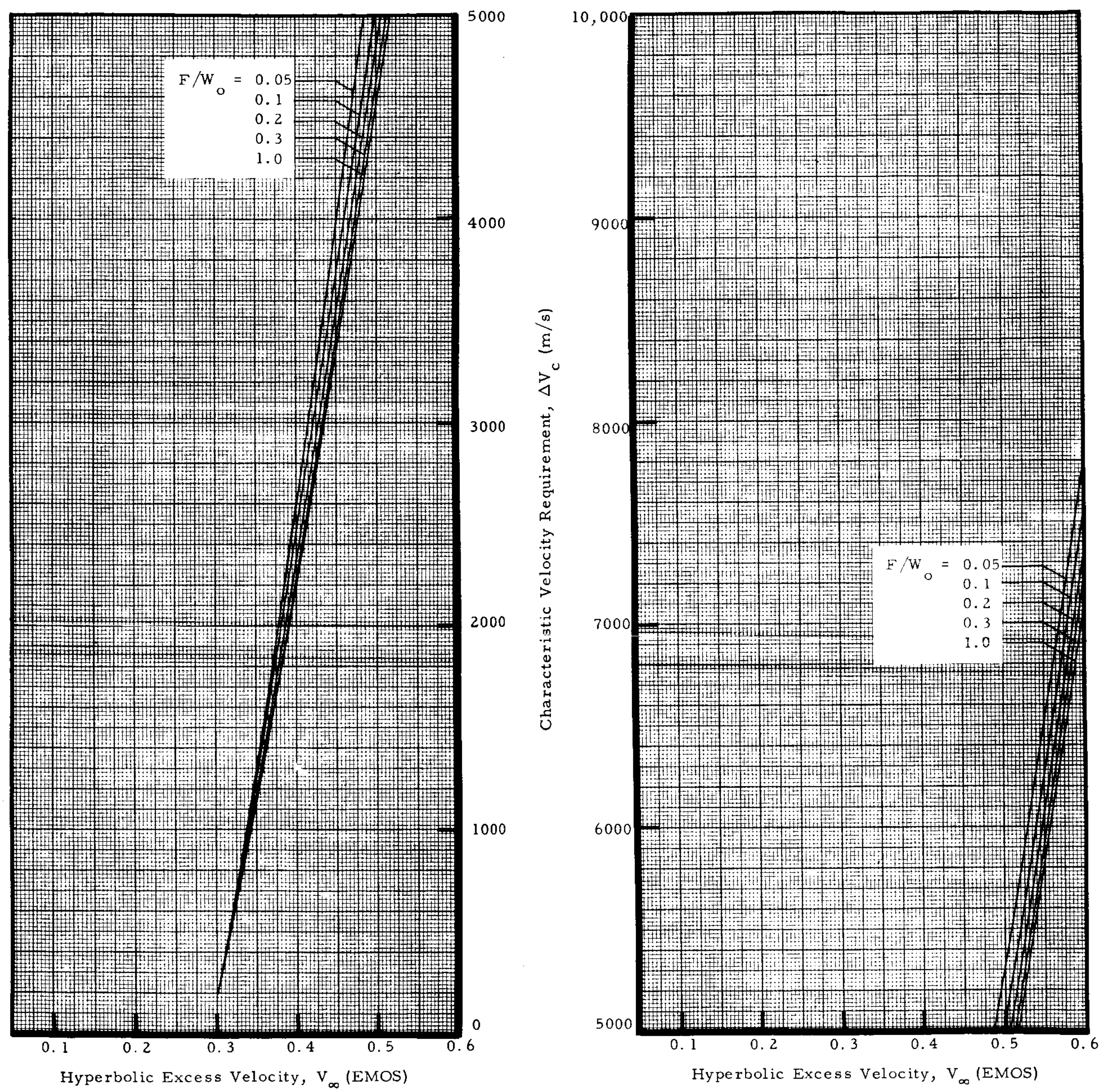
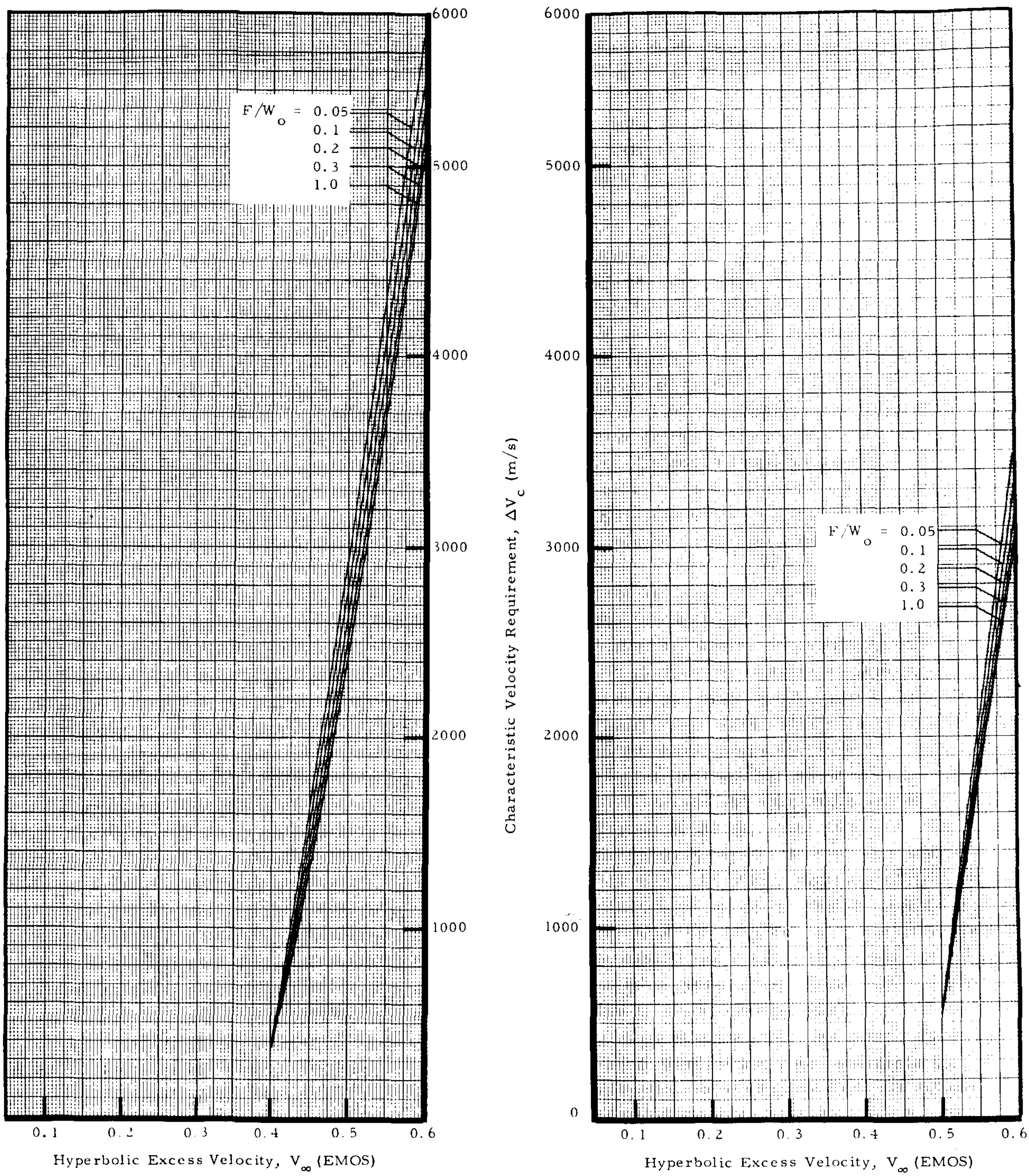


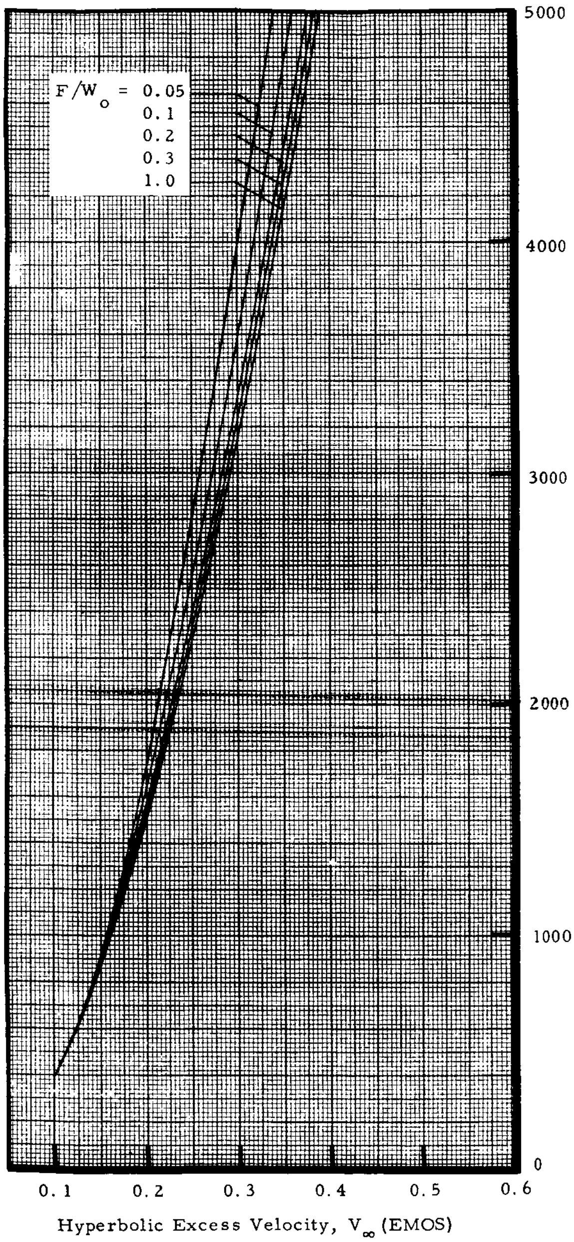
FIGURE 2c. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 320 s
$(V_e)_{max}$ = 14000 m/s



a. $(V_e)_{max}$ = 16000 m/s

b. $(V_e)_{max}$ = 18000 m/s

FIGURE 2d. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 320 s



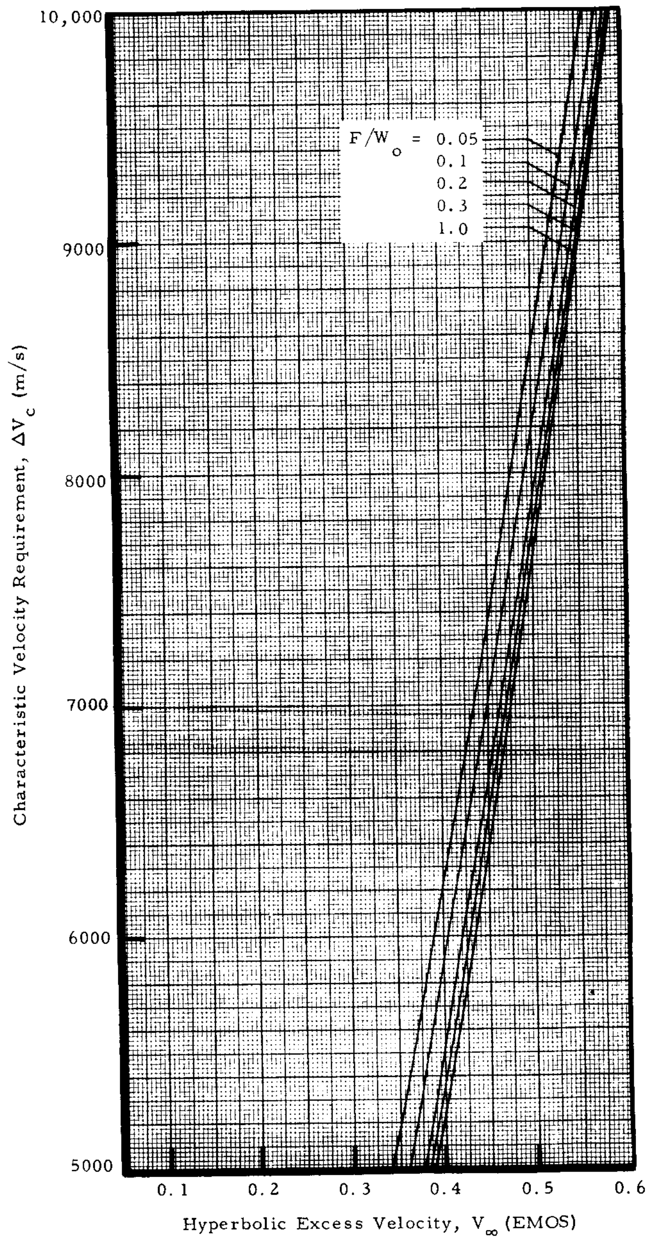


FIGURE 3a. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 330 s
$(V_e)_{max}$ = 11030 m/s

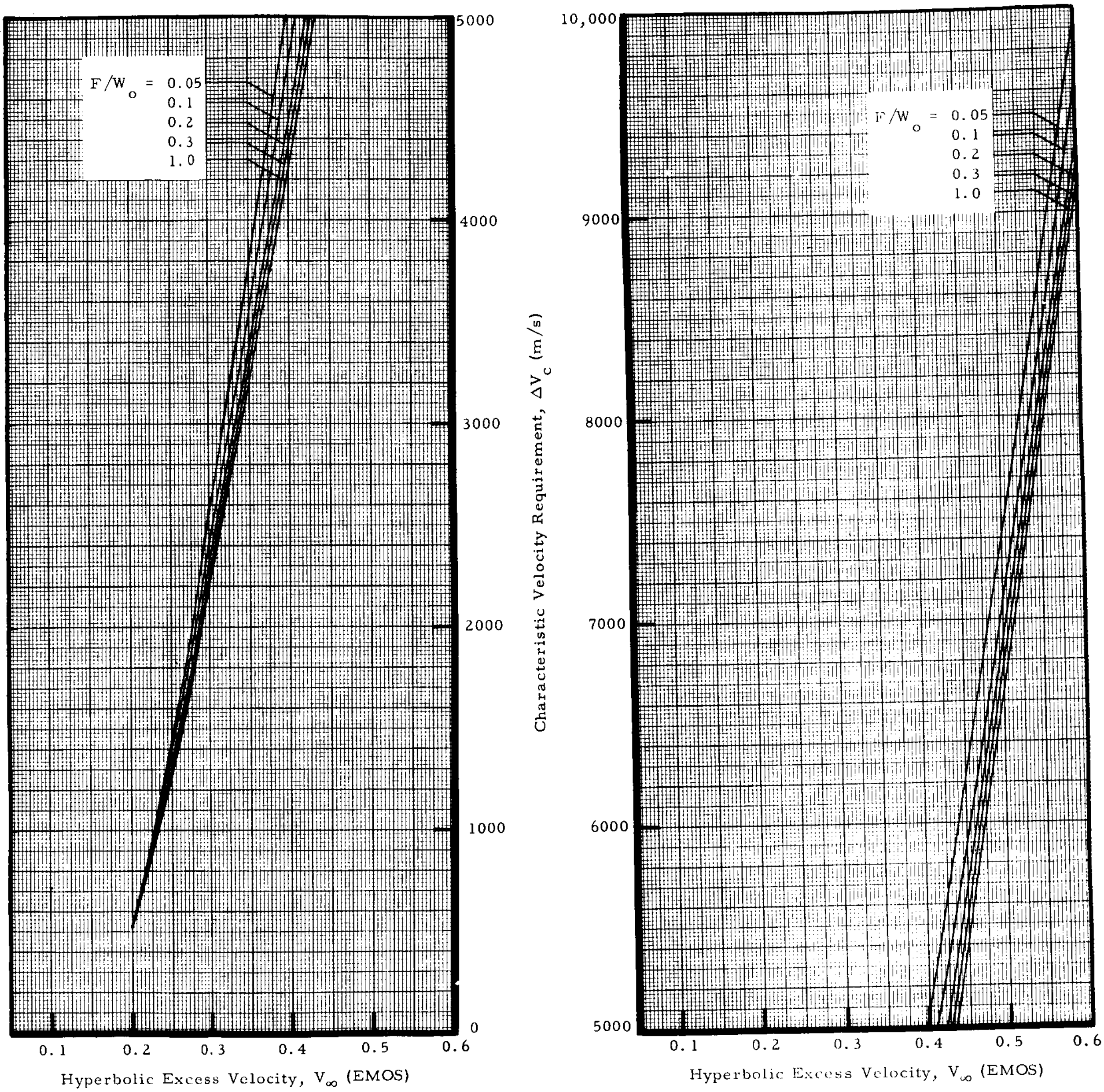


FIGURE 3b. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 330 s $(V_e)_{max}$ = 12000 m/s

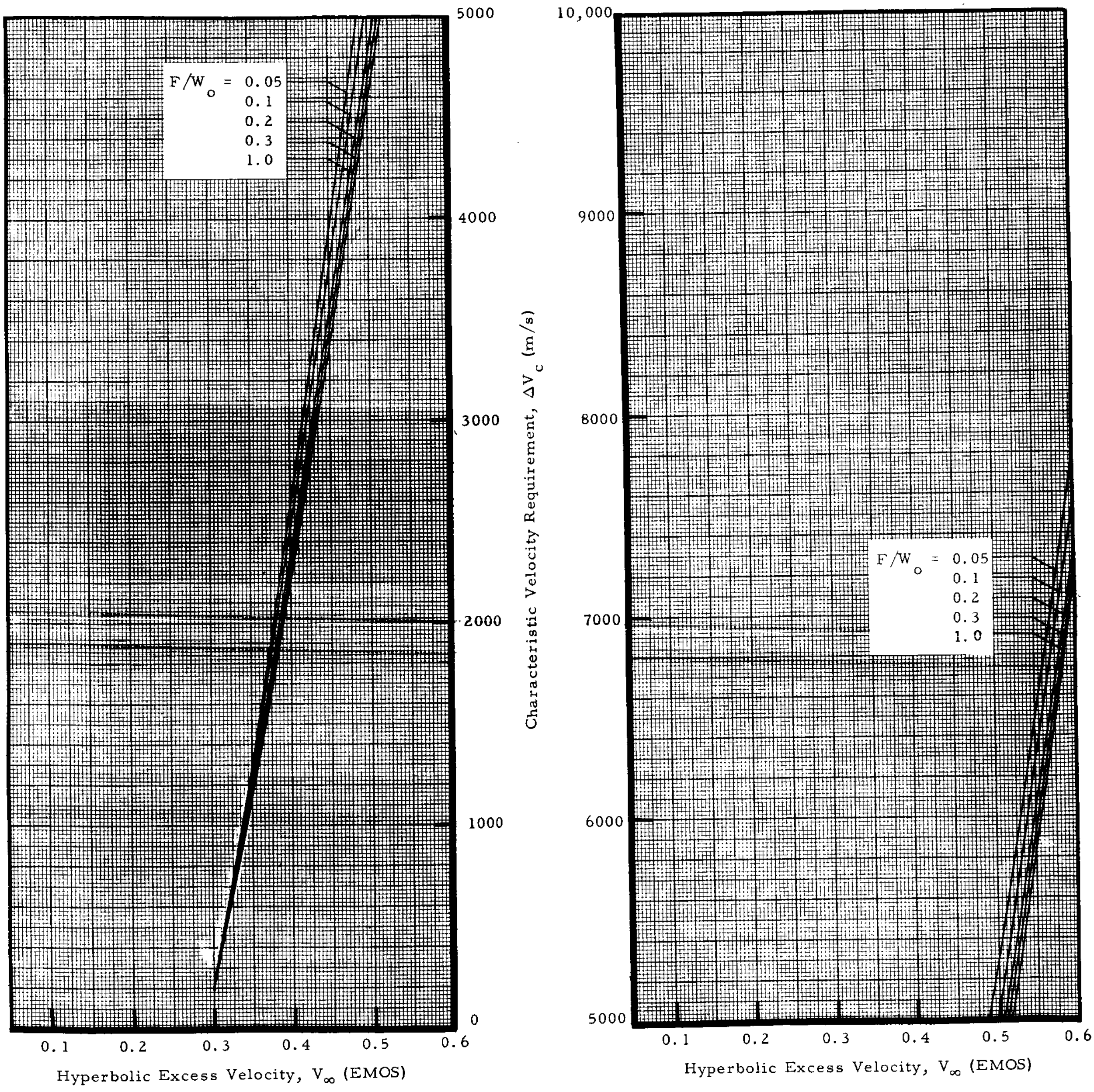


FIGURE 3c. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 330 s
$(V_e)_{max}$ = 14000 m/s

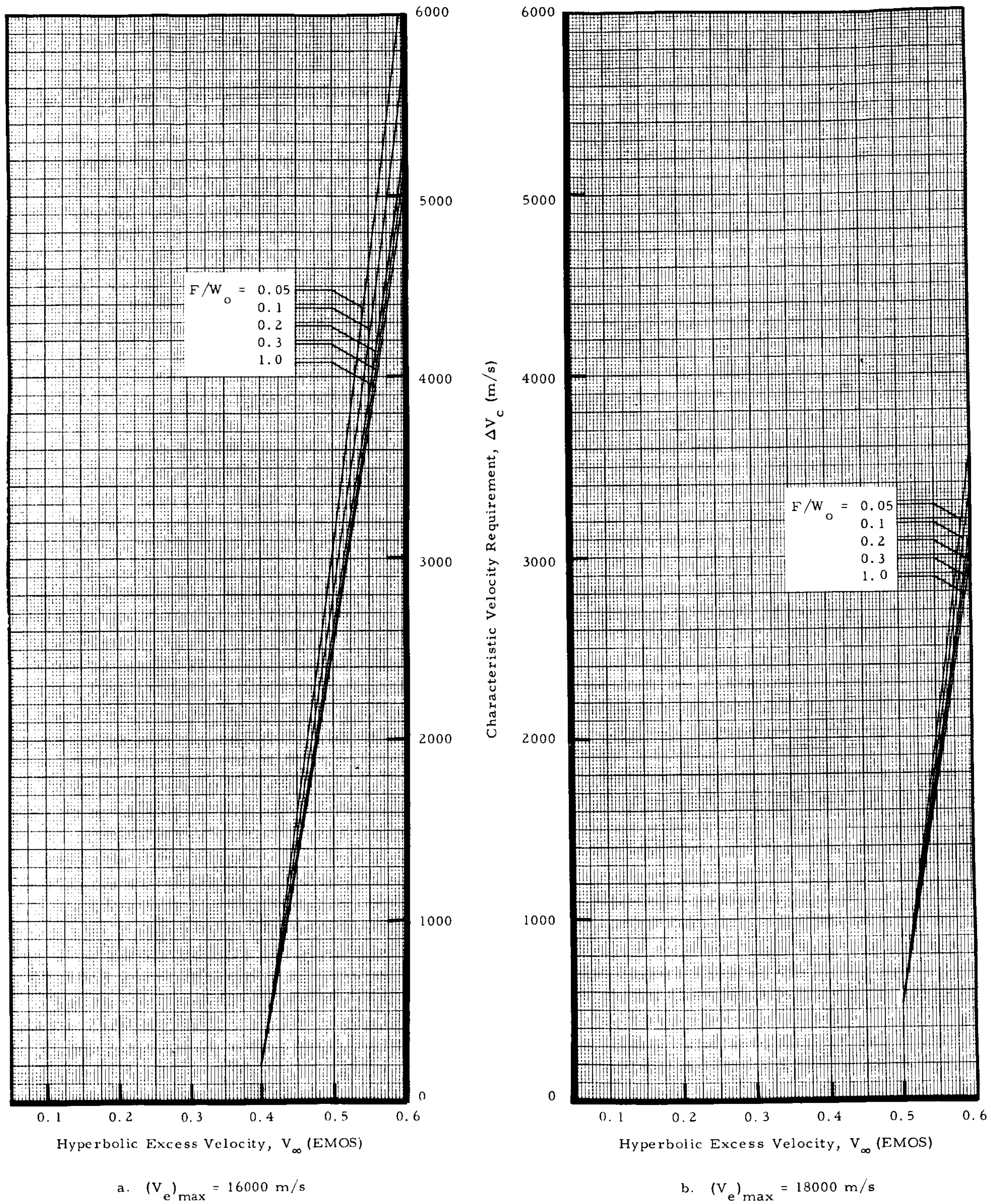


FIGURE 3d. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 330 s

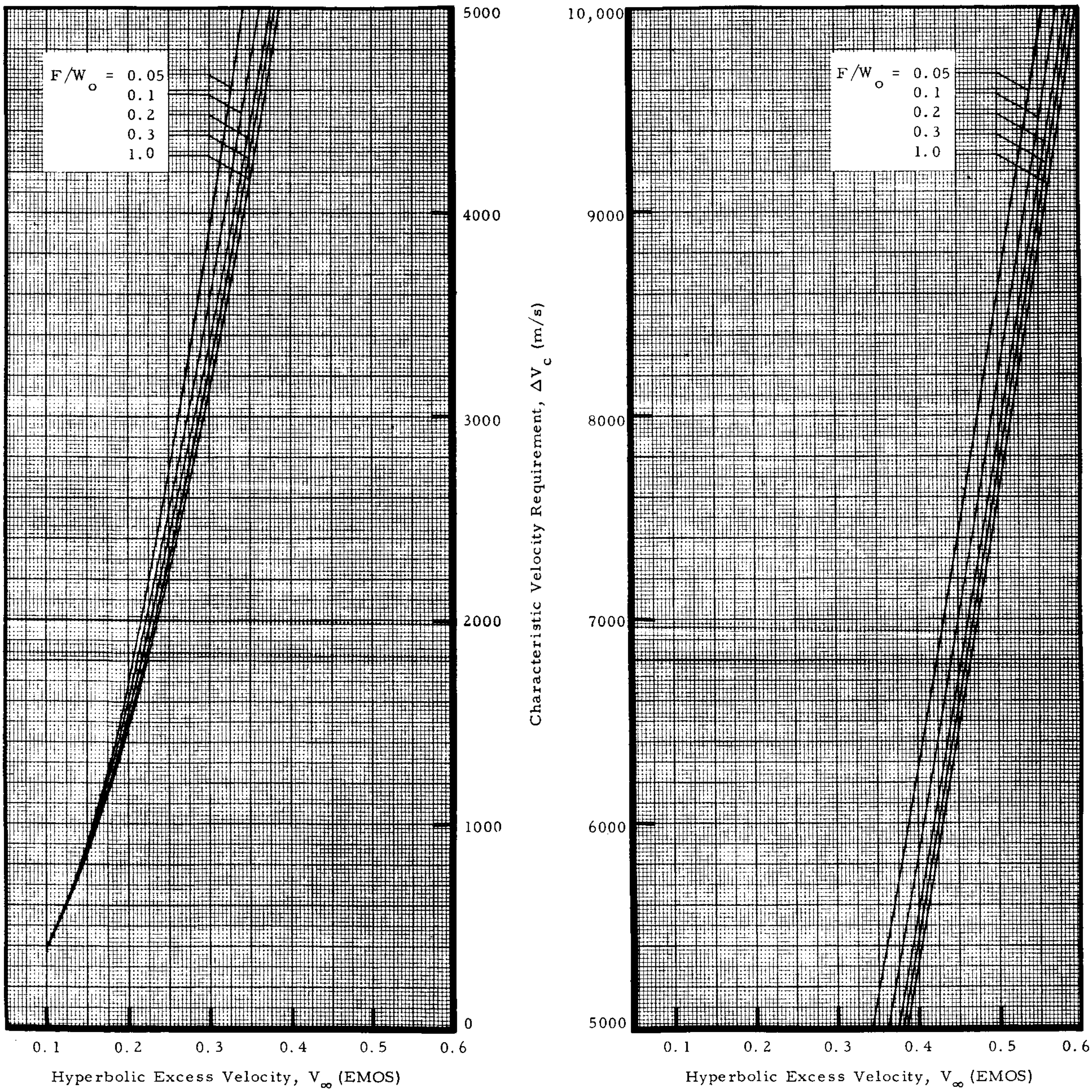


FIGURE 4a. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 340 s
$(V_e)_{max}$ 11030 m/s

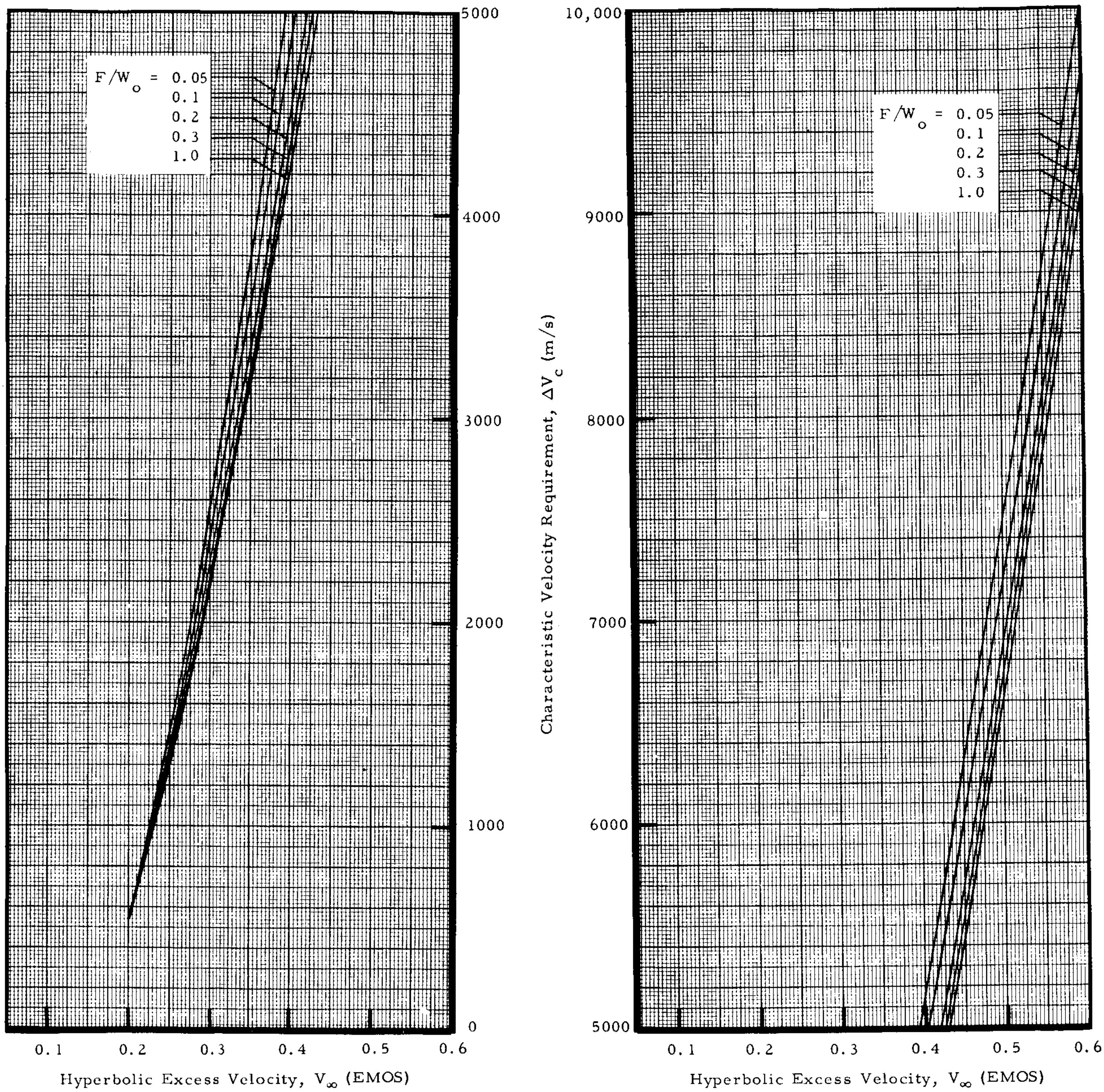


FIGURE 4b. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 340 s
$(V_e)_{max}$ = 12000 m/s

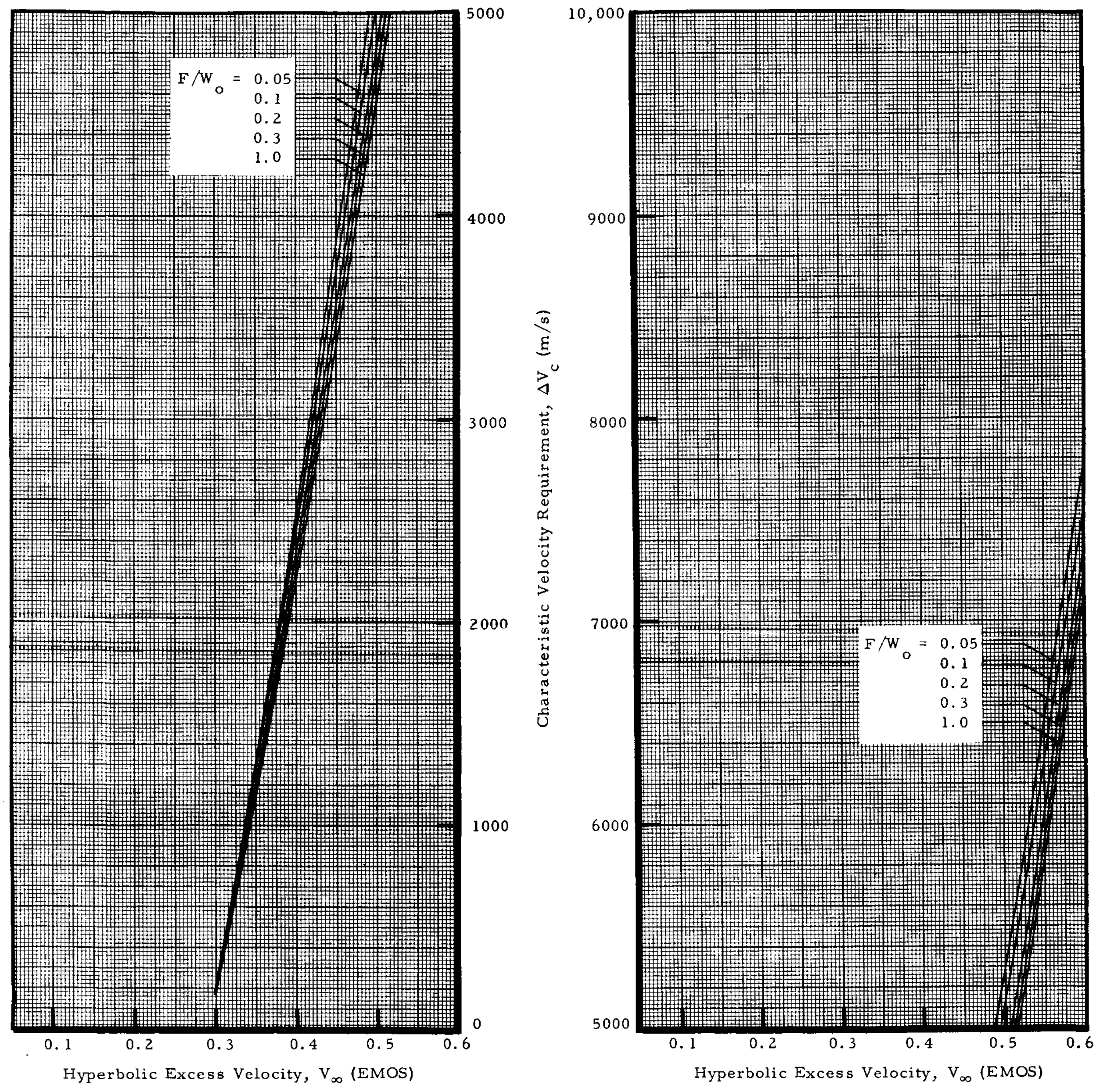


FIGURE 4c. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 340 s
$(V_e)_{max}$ = 14000 m/s

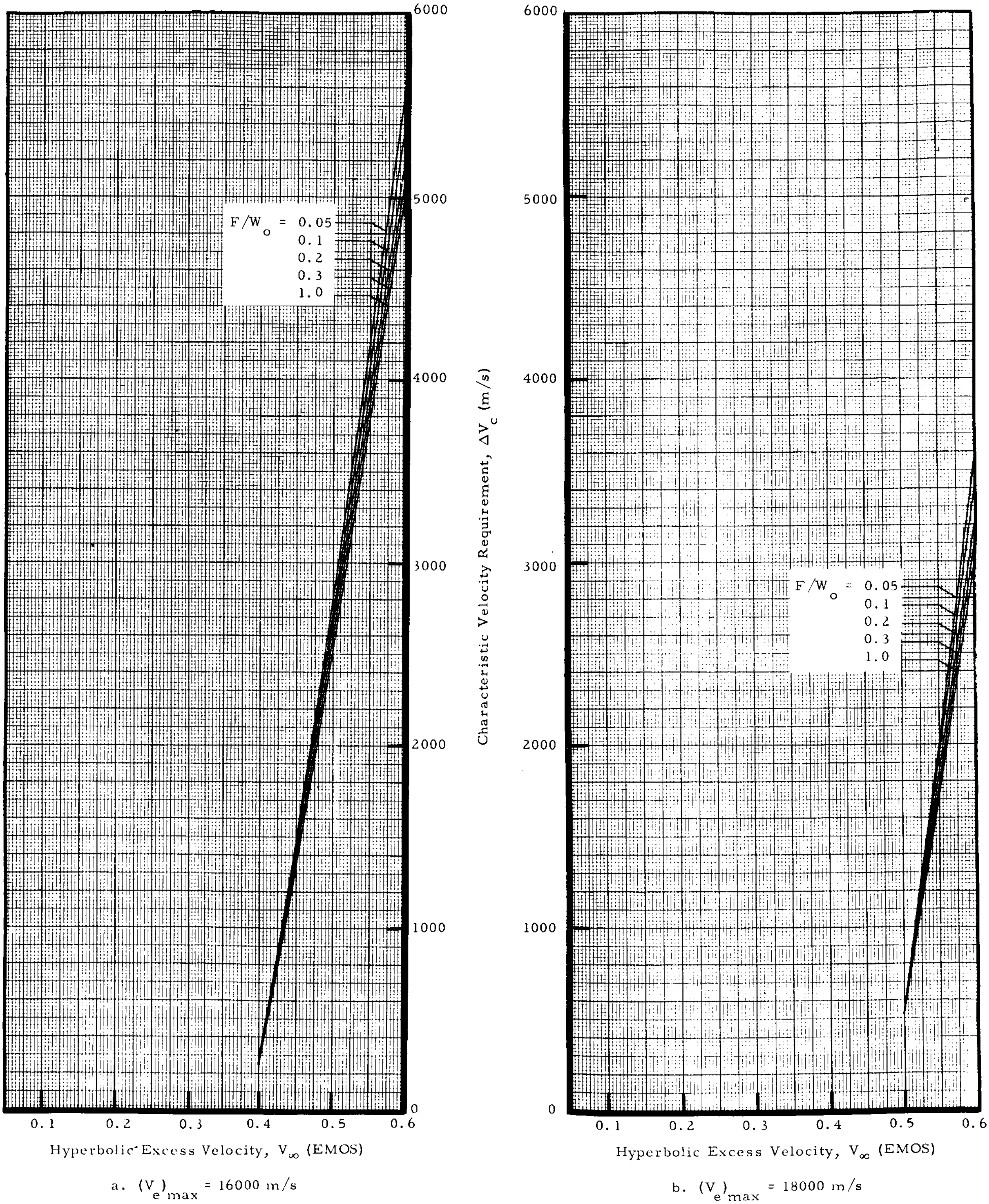


FIGURE 4d. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 340 s

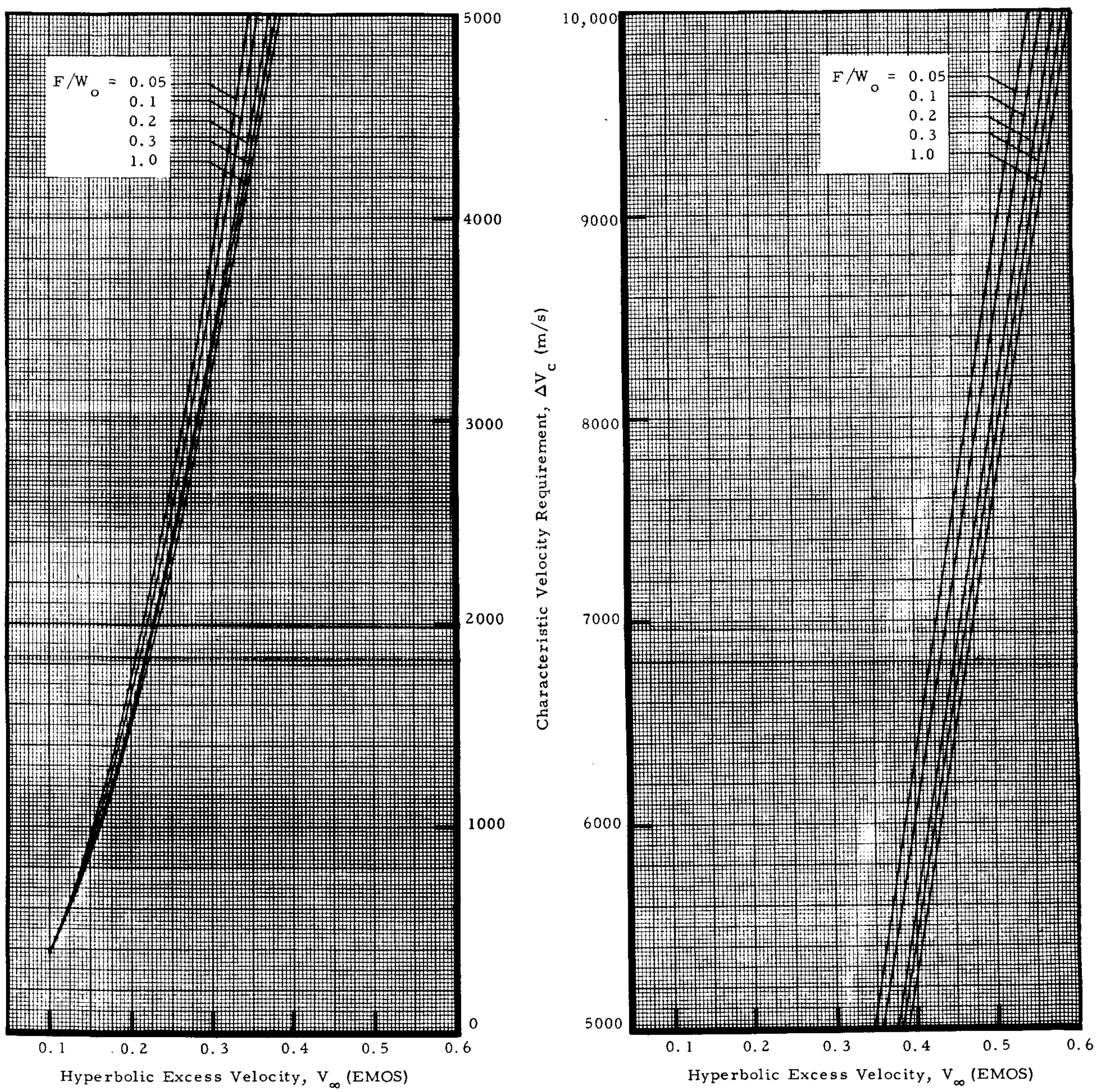


FIGURE 5a. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 420 s
$(V_e)_{max}$ = 11030 m/s

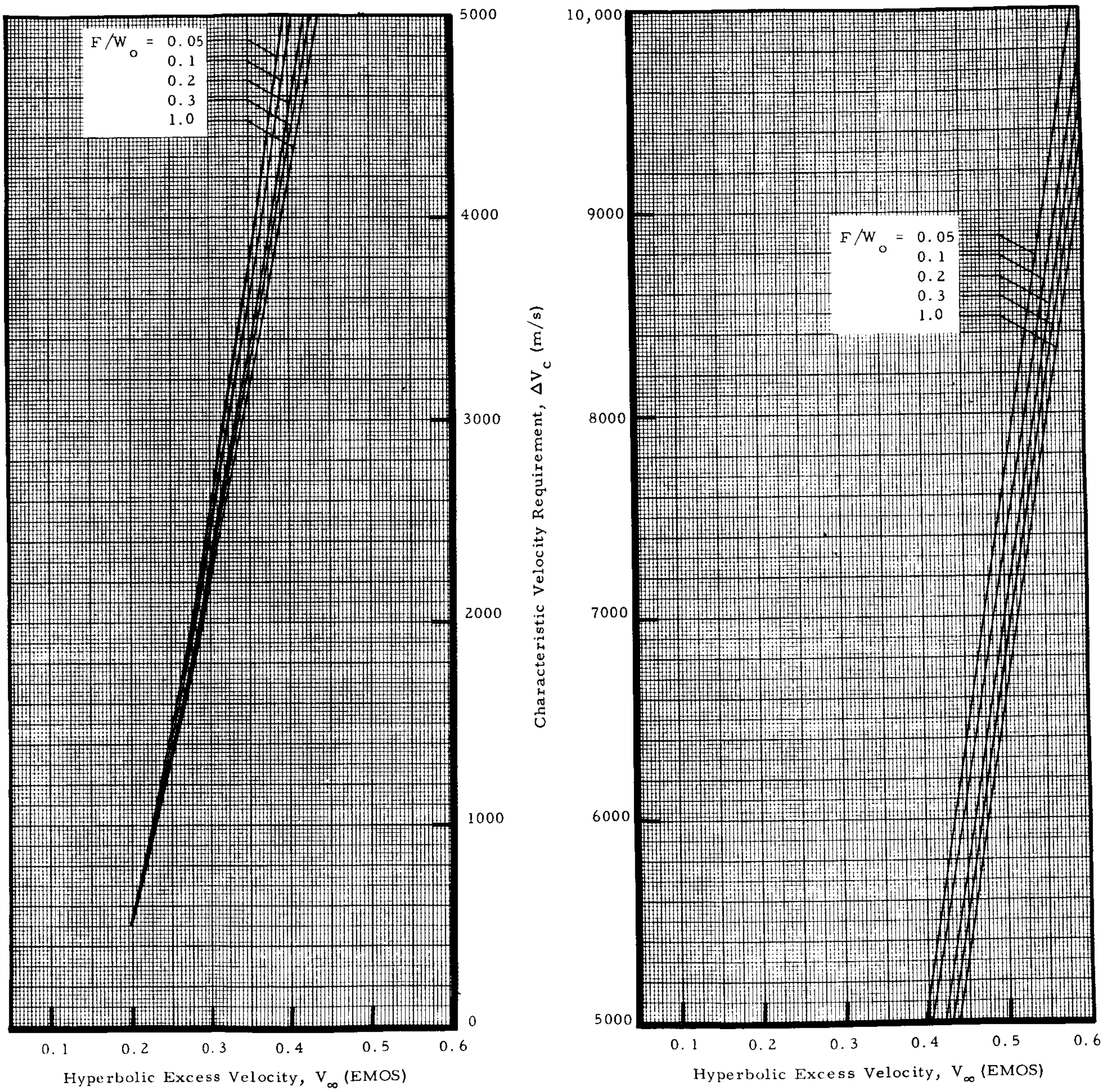


FIGURE 5b. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 420 s
$(V_e)_{max}$ = 12000 m/s

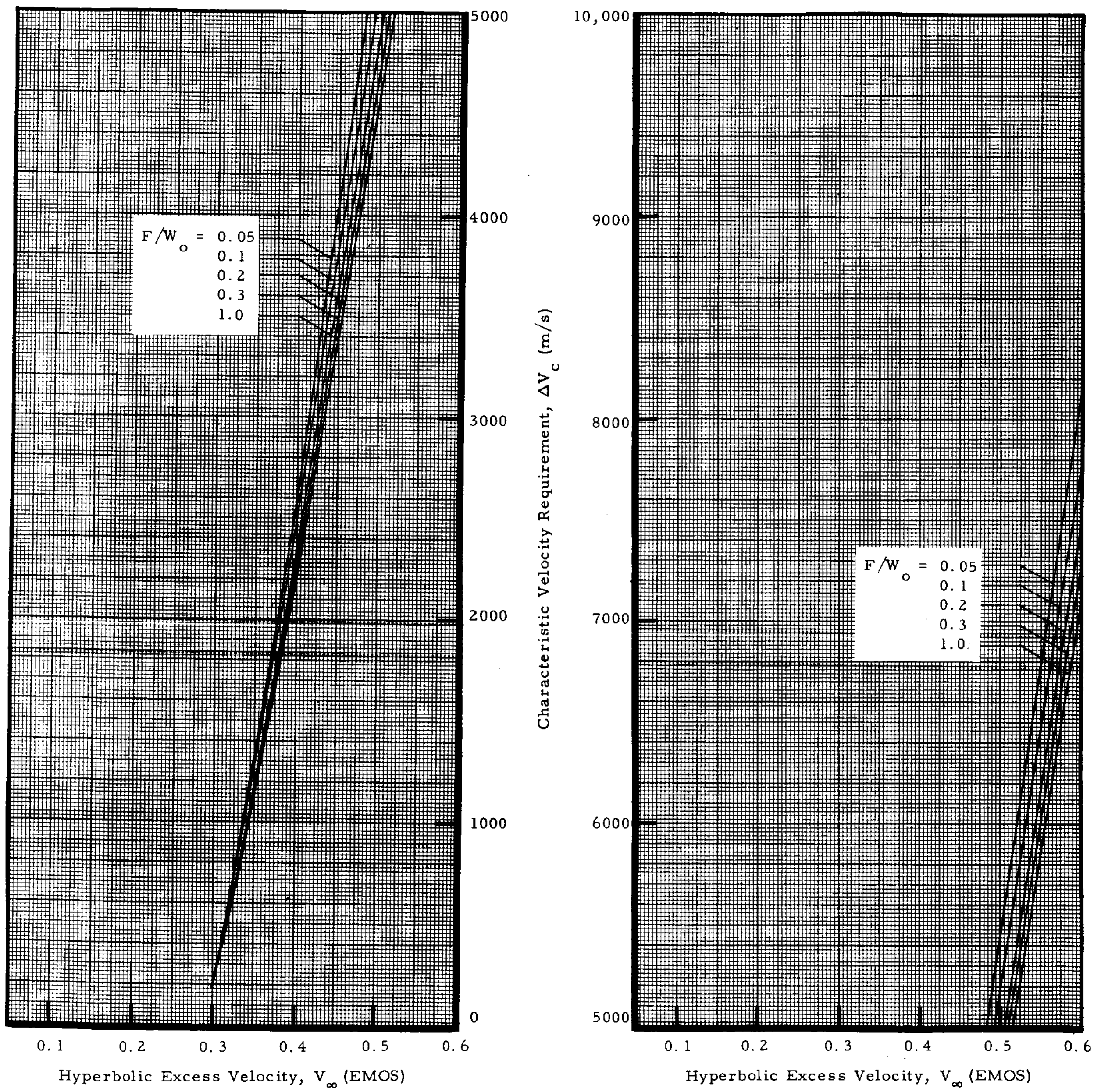


FIGURE 5c. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 420 s
$(V_e)_{max}$ = 14000 m/s

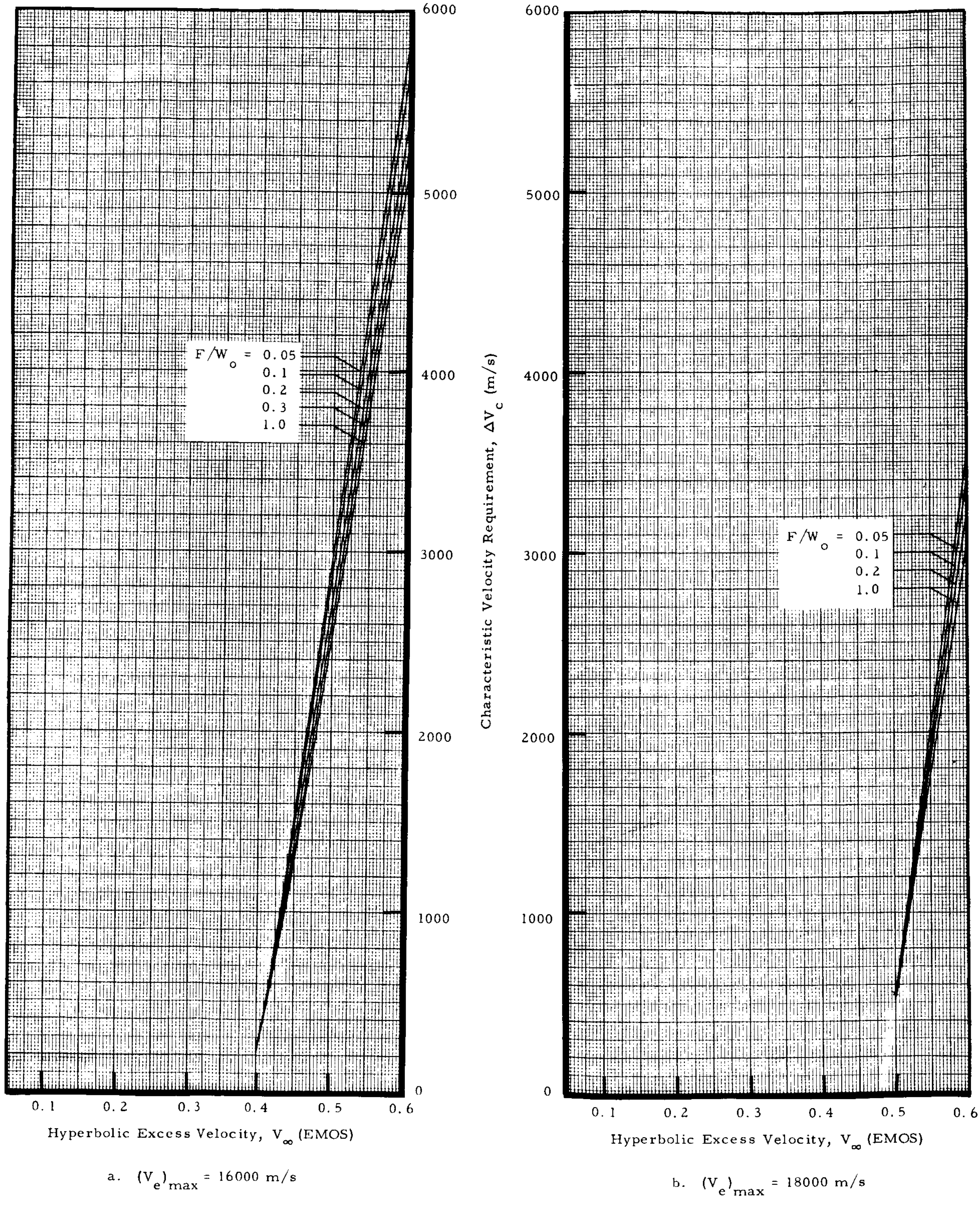


FIGURE 5d. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 420 s

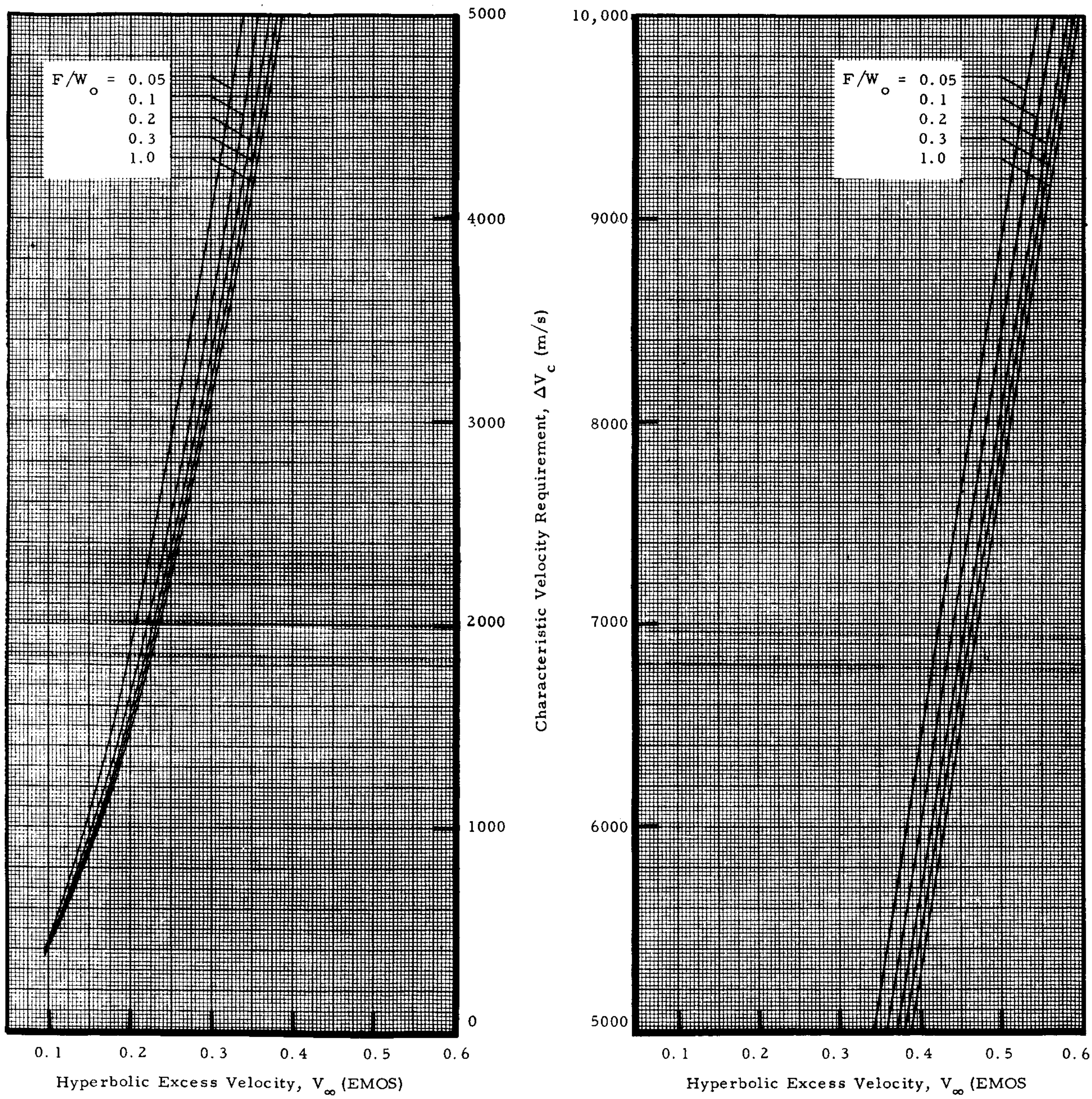


FIGURE 6a. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 430 s $(V_e)_{max}$ = 11030 m/s

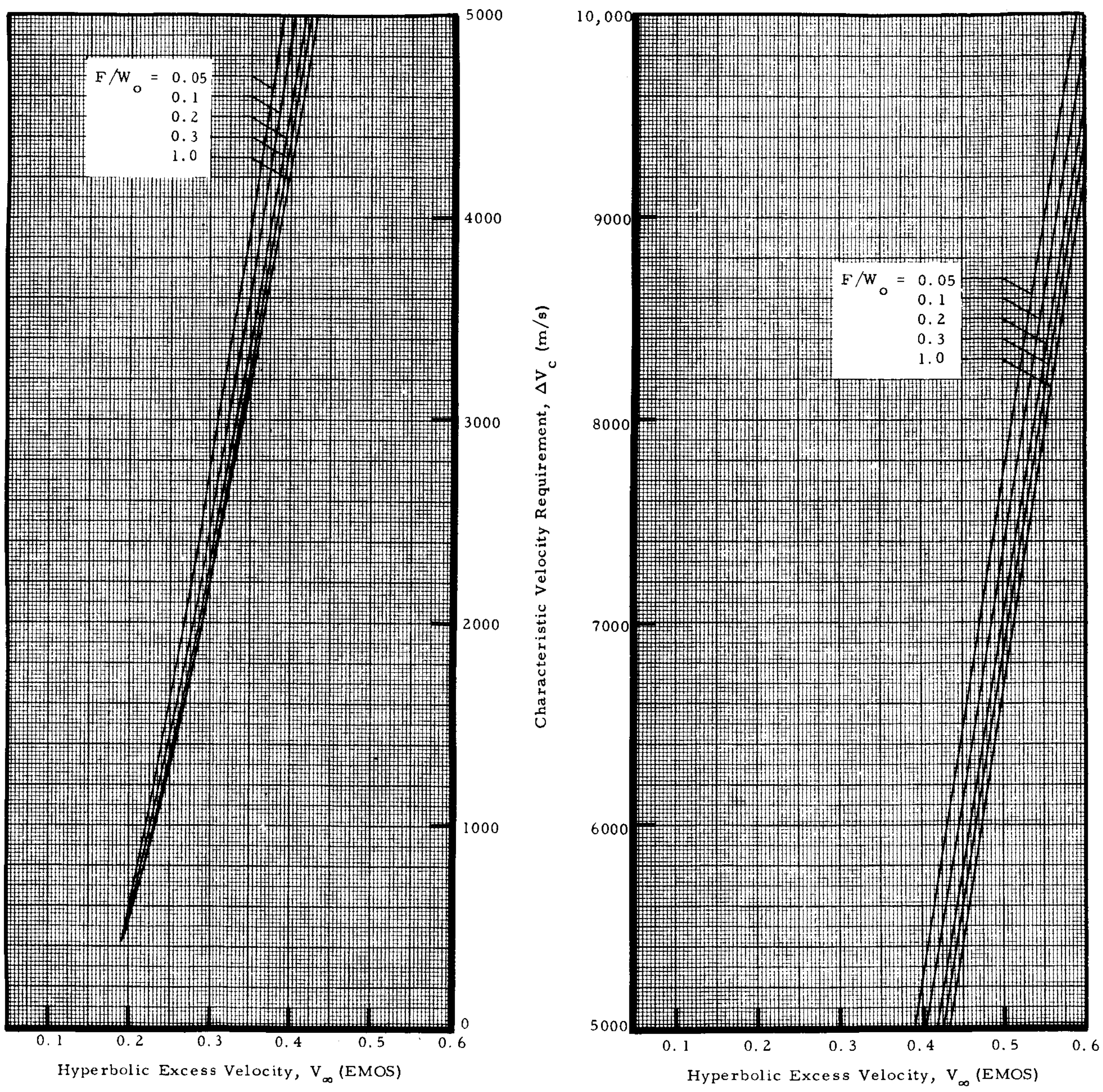


FIGURE 6b. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 430 s
$(V_e)_{max}$ = 12000 m/s

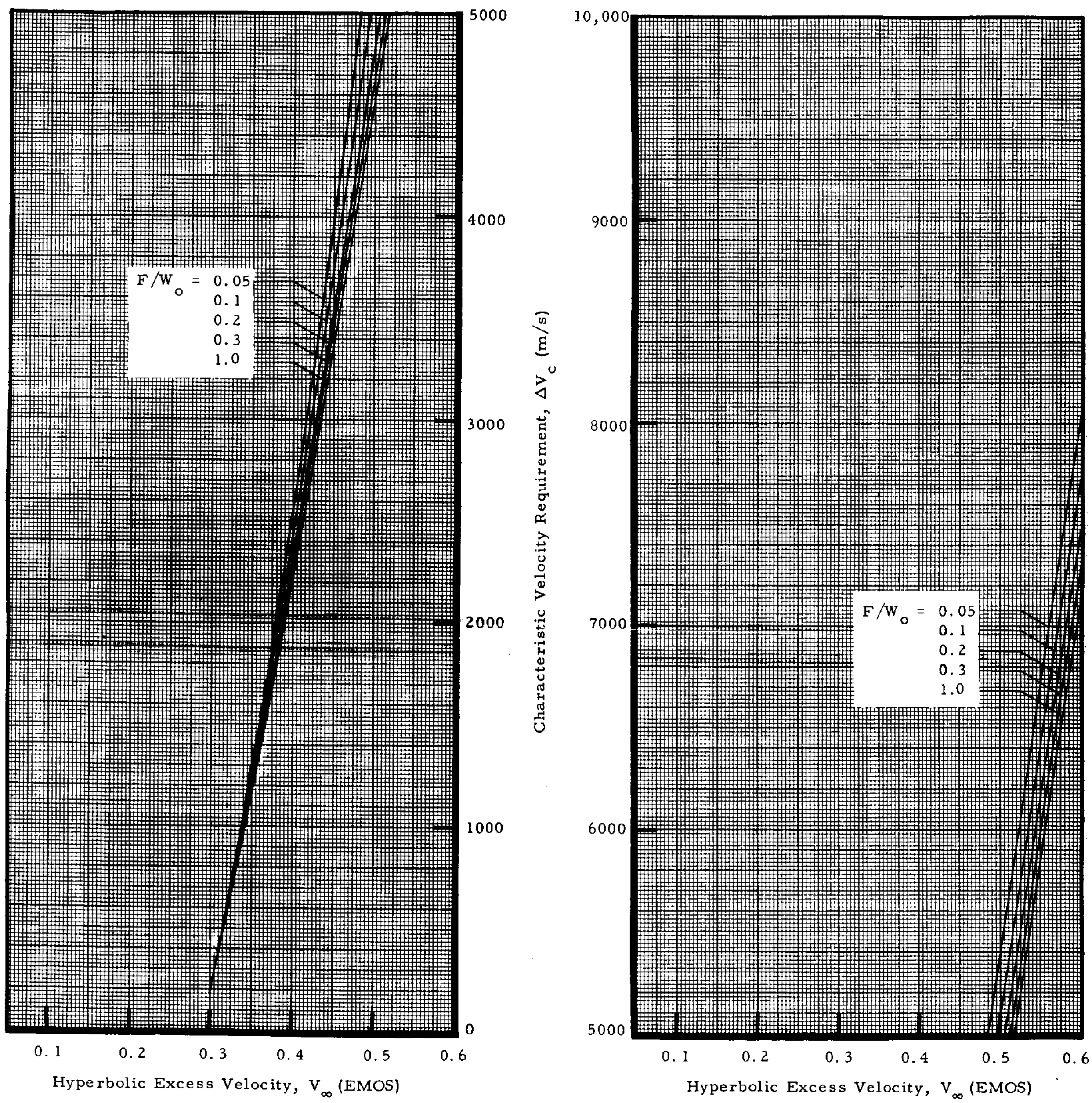


FIGURE 6c. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 430 s
$(V_e)_{max}$ = 14000 m/s

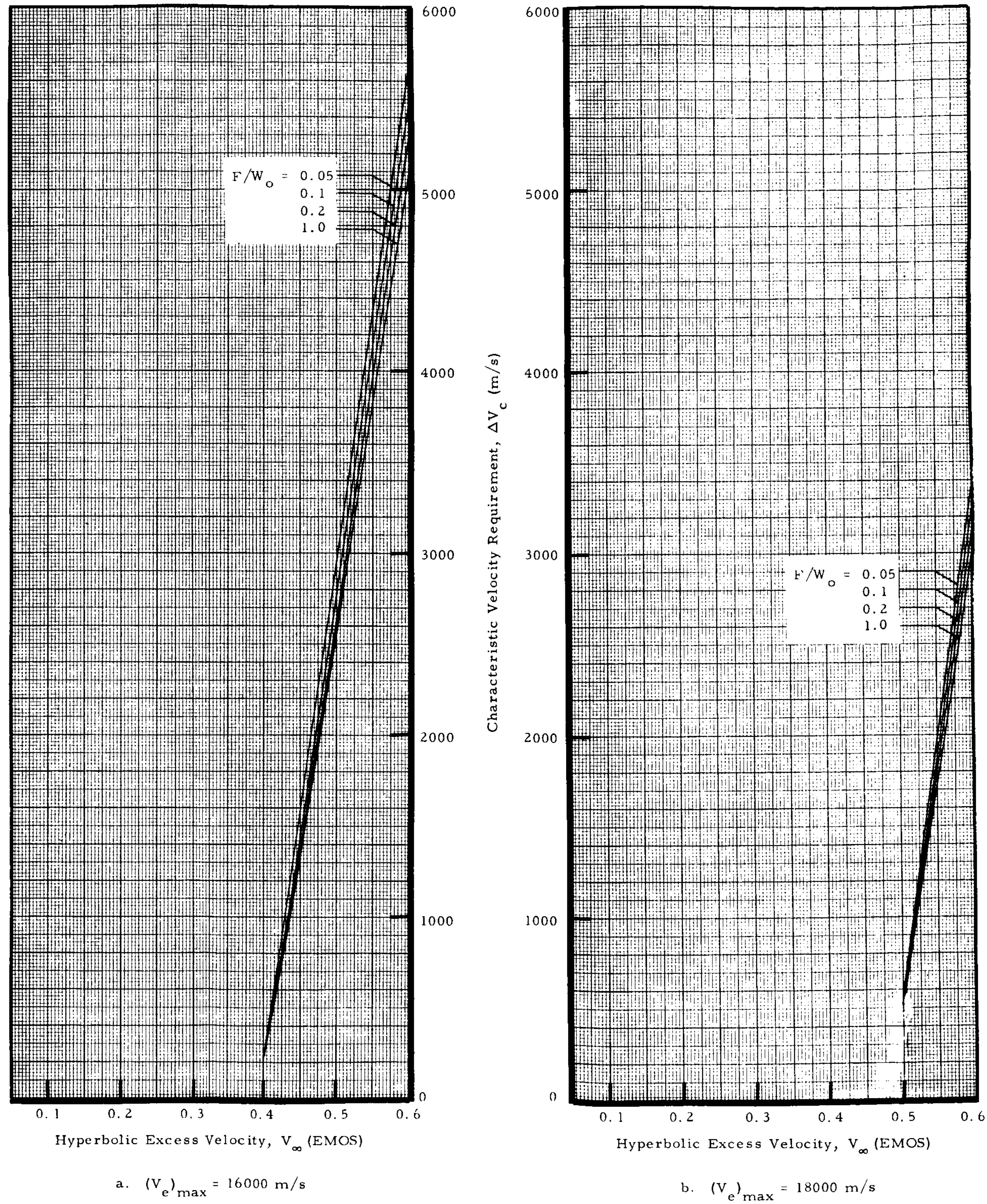


FIGURE 6d. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 430 s

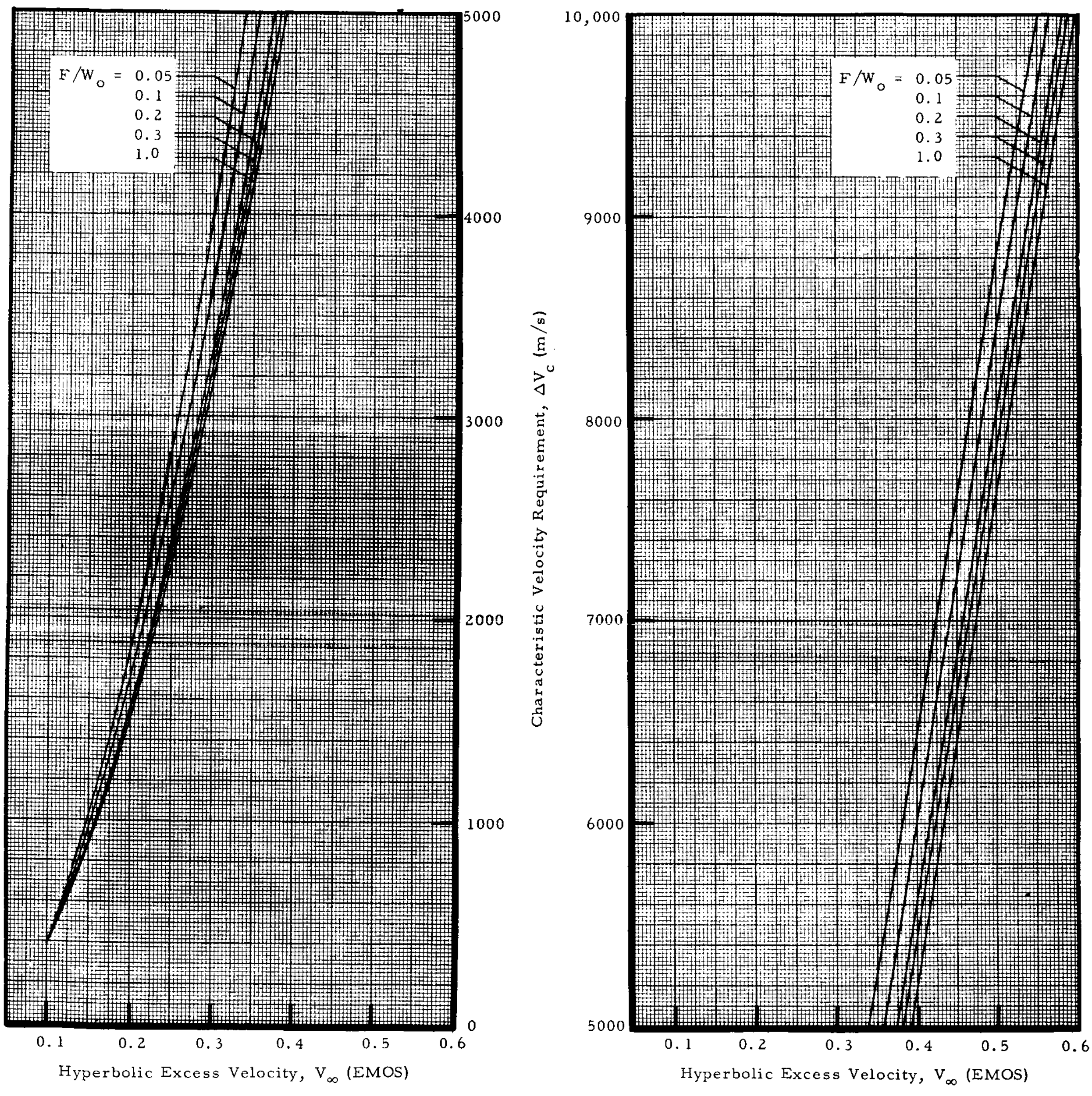


FIGURE 7a. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 440 s
$(V_e)_{max}$ = 11030 m/s

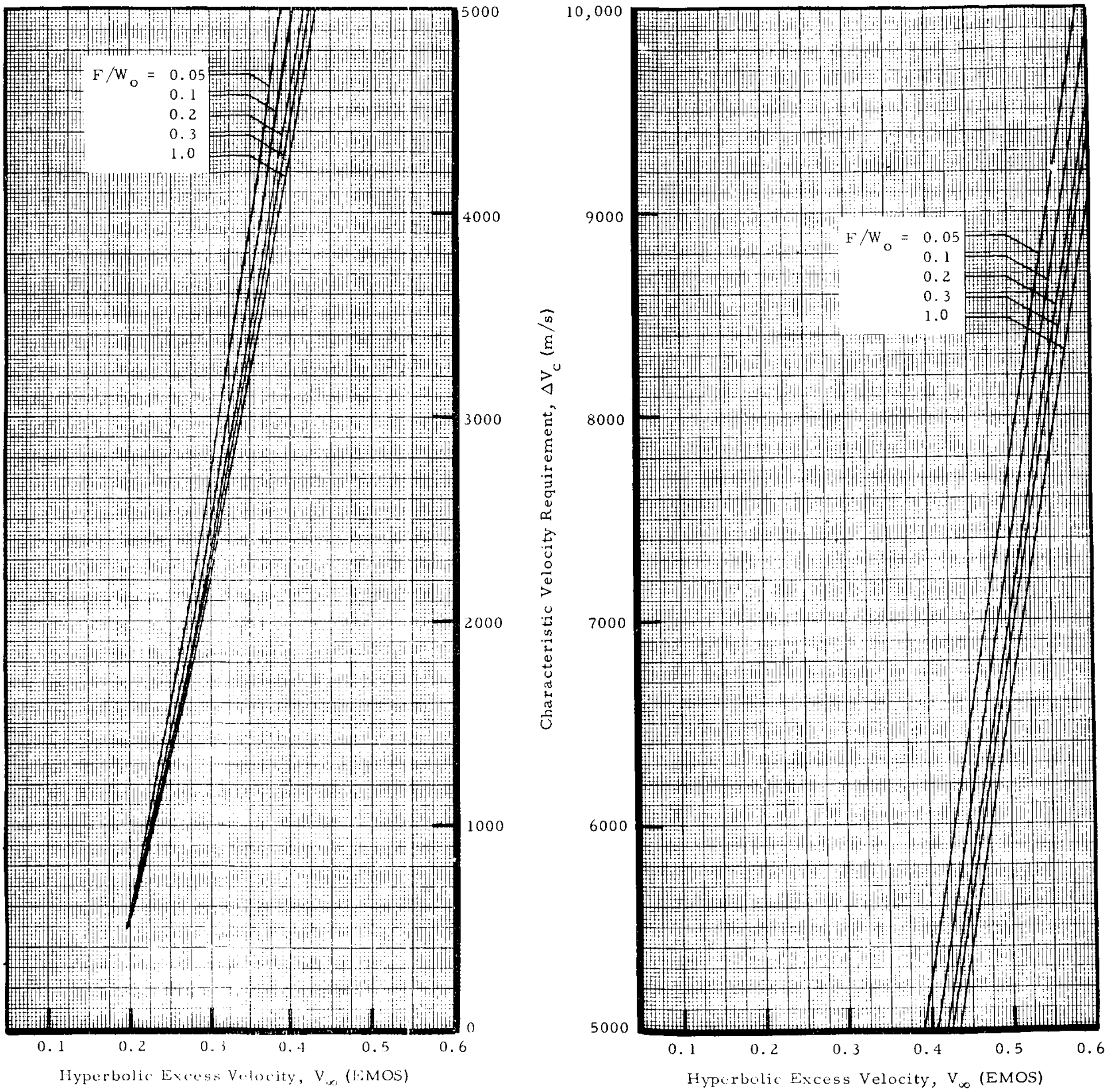


FIGURE 7b. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 440 s
$(V_e)_{max}$ = 12000 m/s

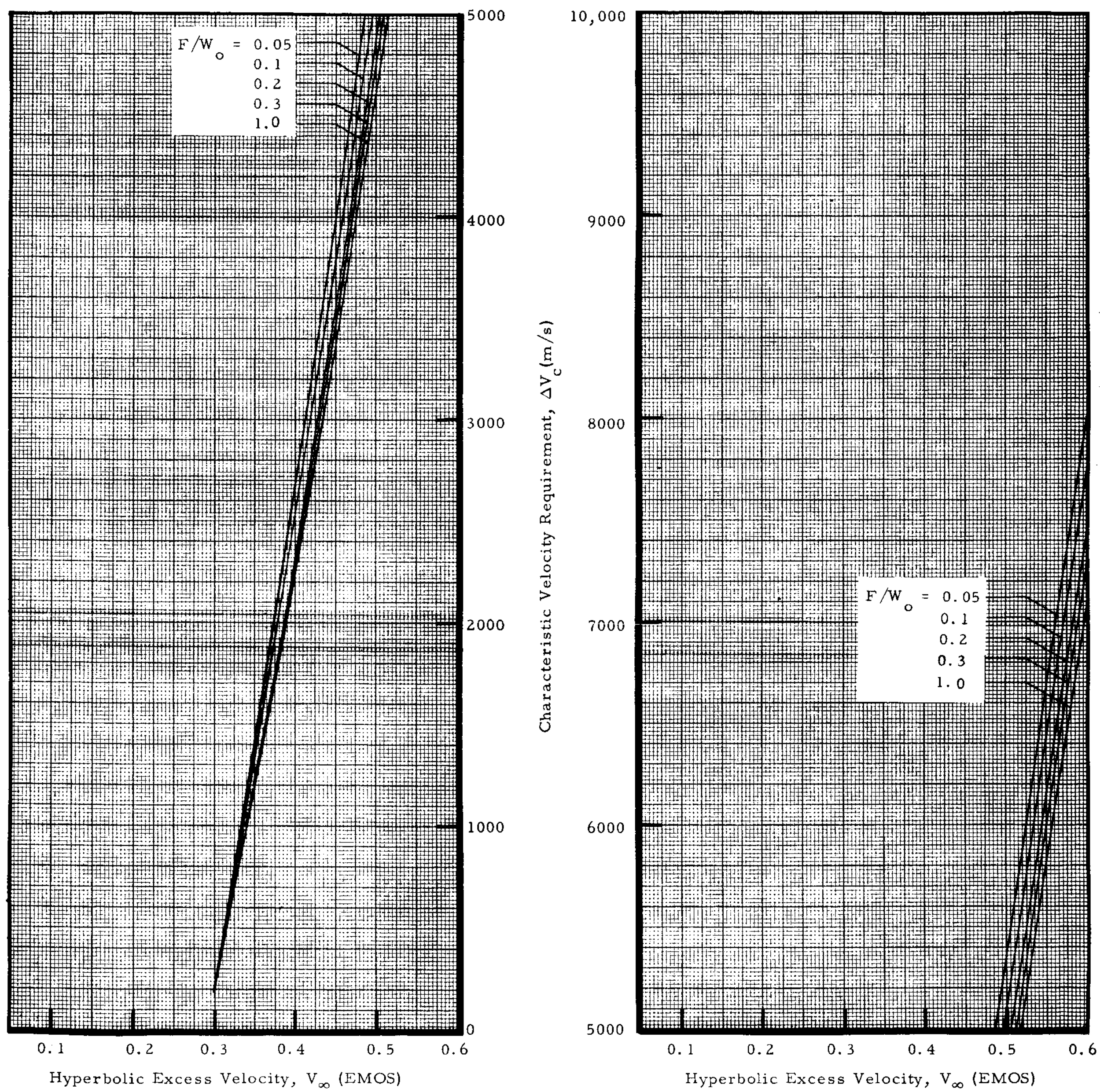


FIGURE 7c. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 440 s
$(V_e)_{max}$ = 14000 m/s

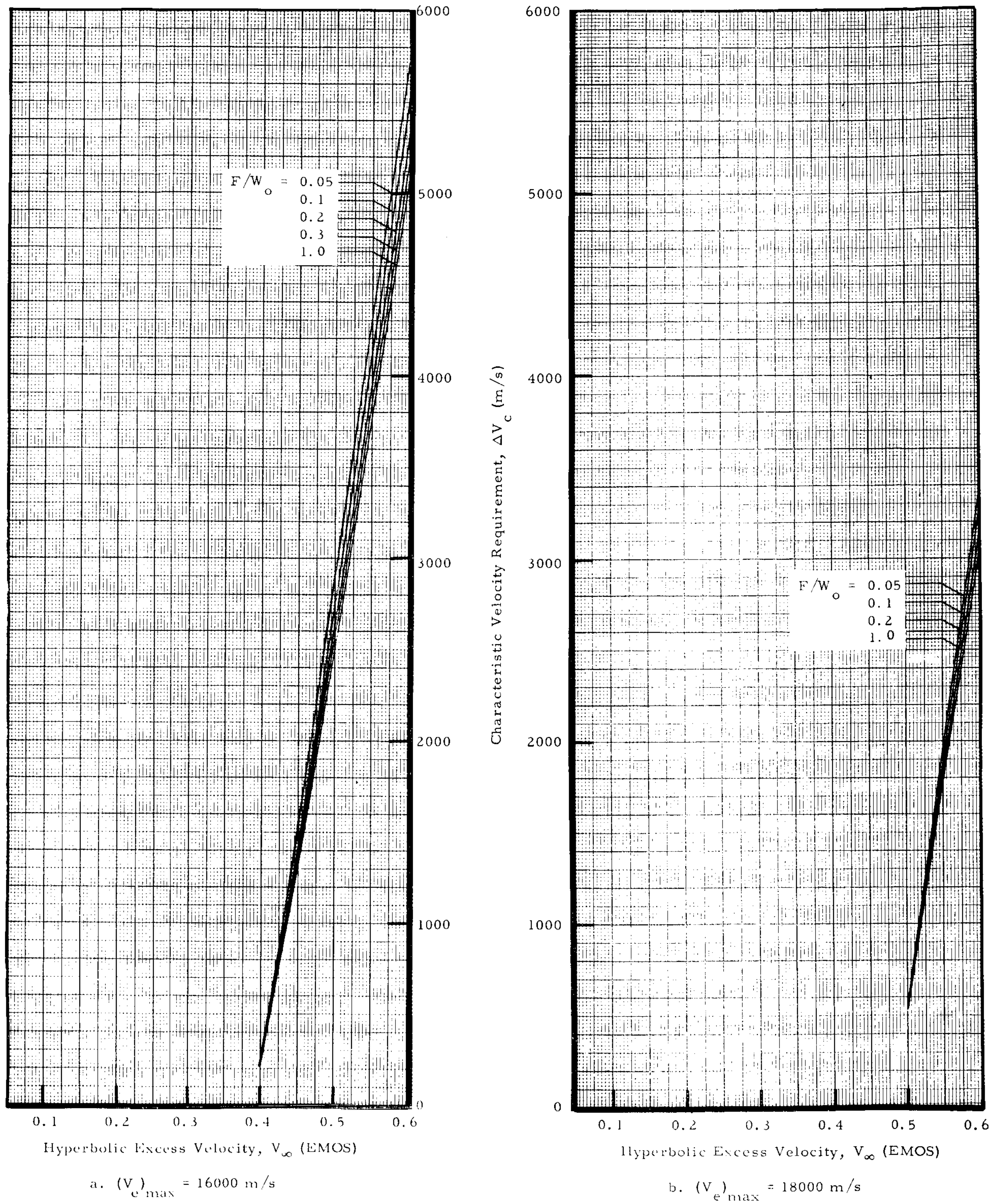


FIGURE 7d. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 440 s

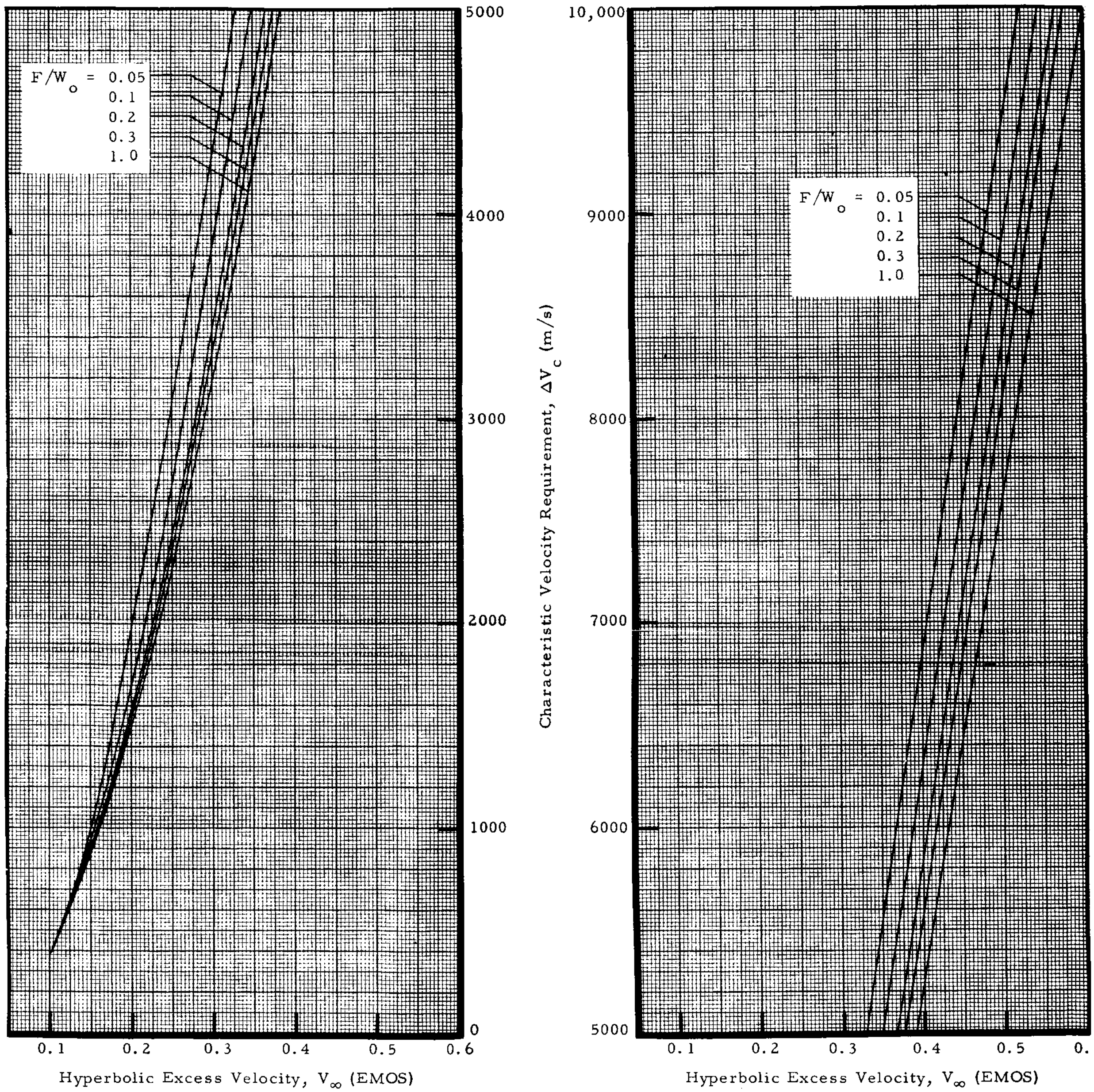


FIGURE 8a. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 775 s
$(V_e)_{max}$ = 11030 m/s

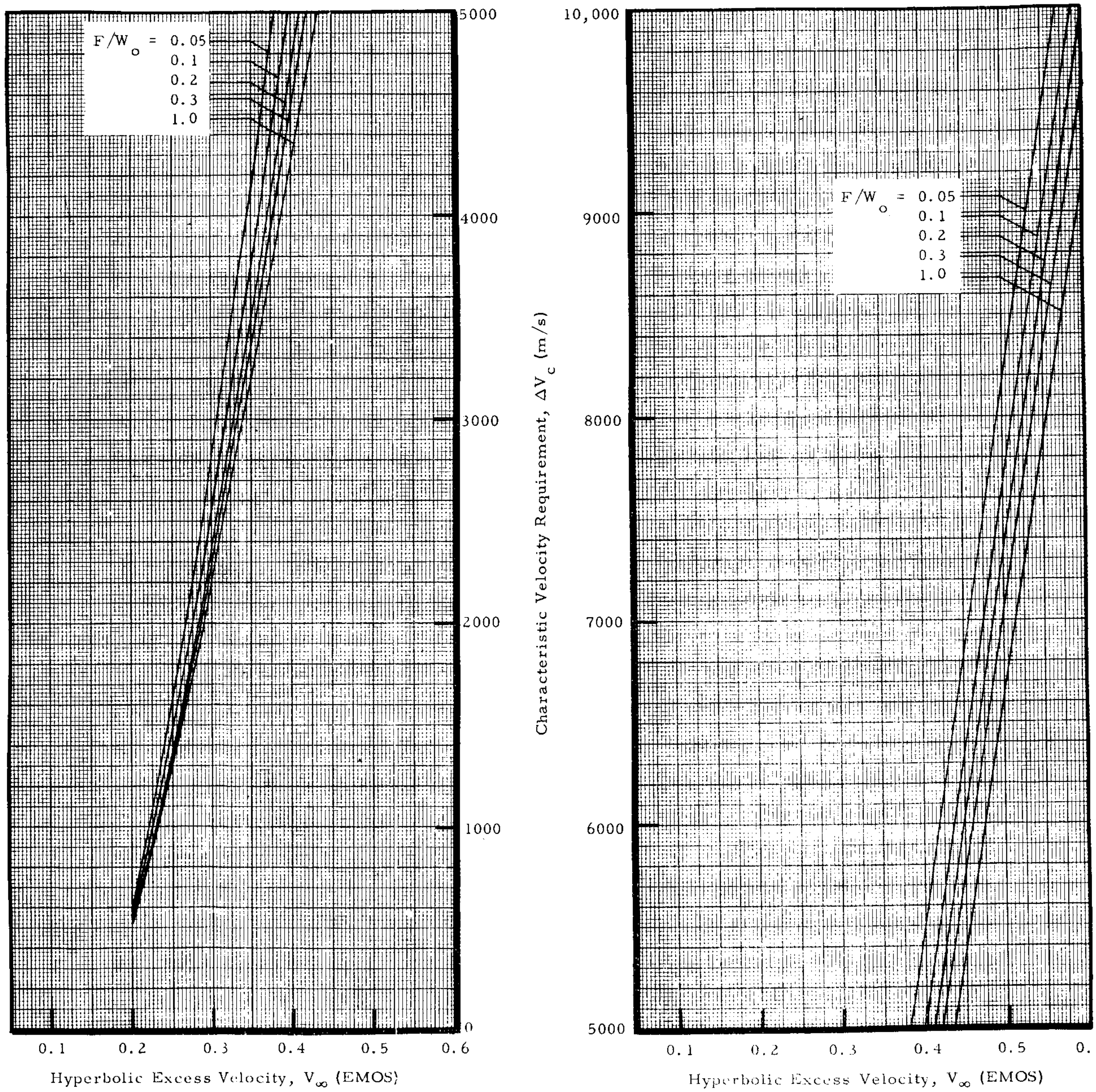


FIGURE 8b. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 775 s
$(V_e)_{max}$ = 12000 m/s

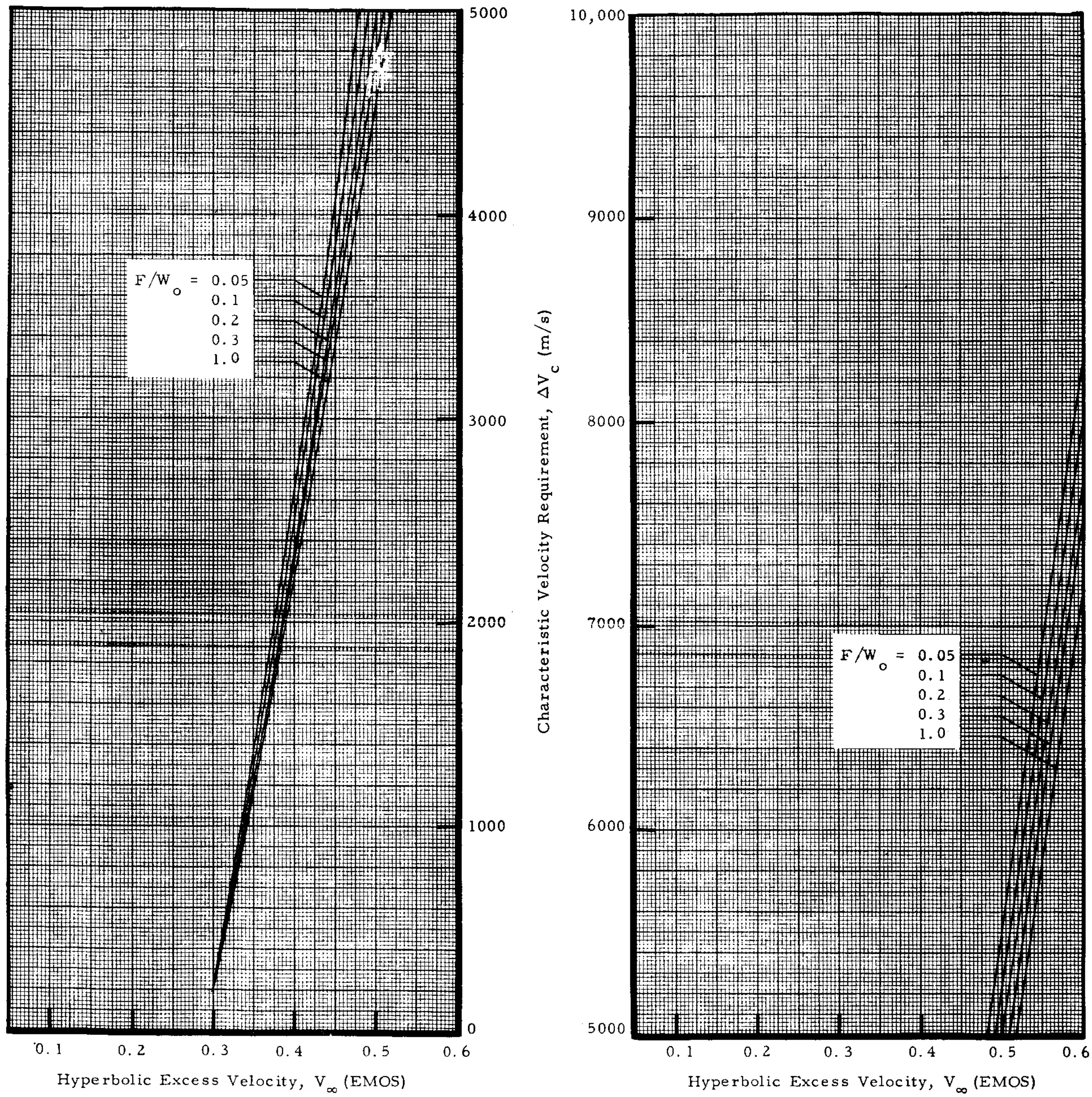


FIGURE 8c. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 775 s
$(V_e)_{max}$ = 14000 m/s

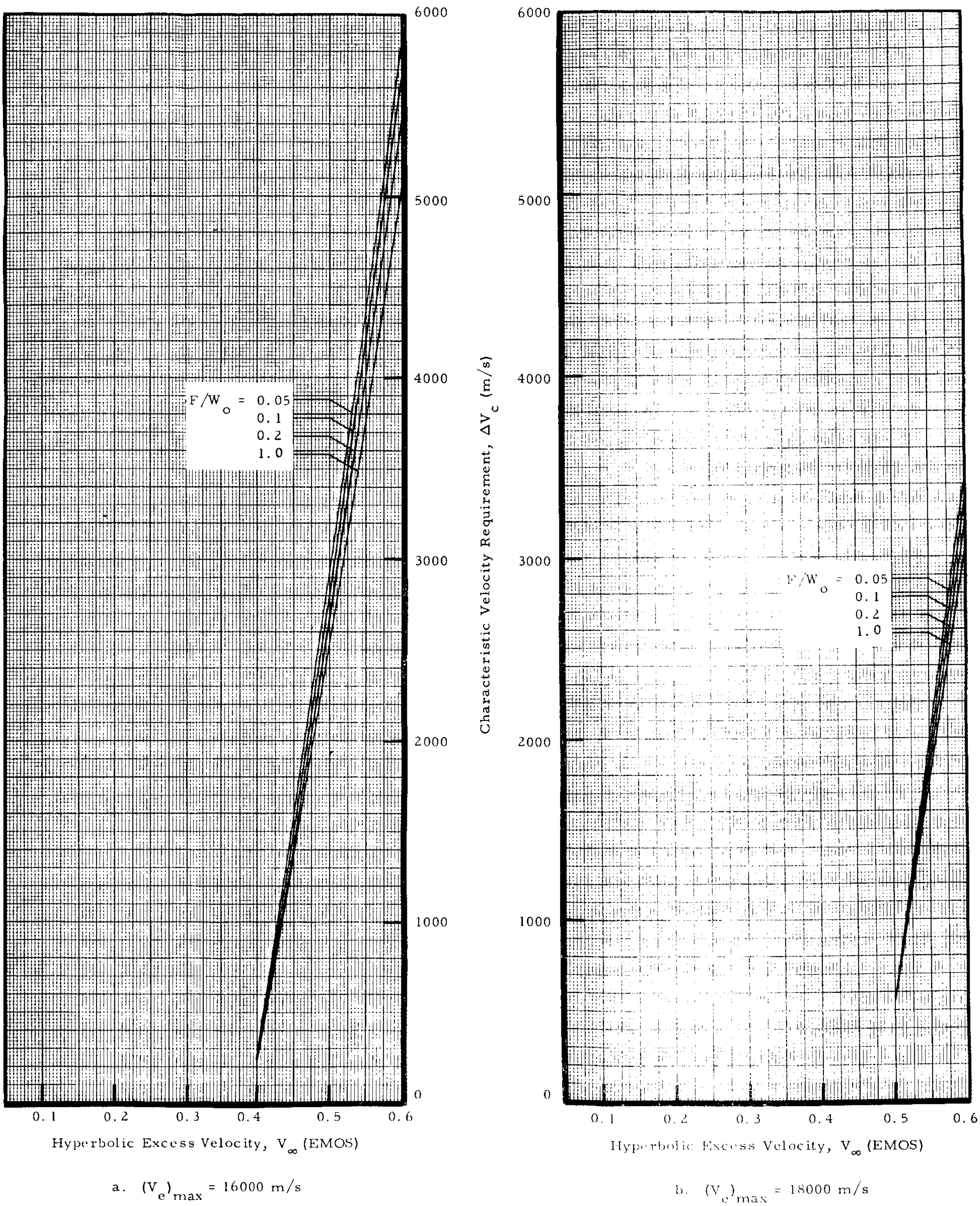


FIGURE 8d. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 775 s

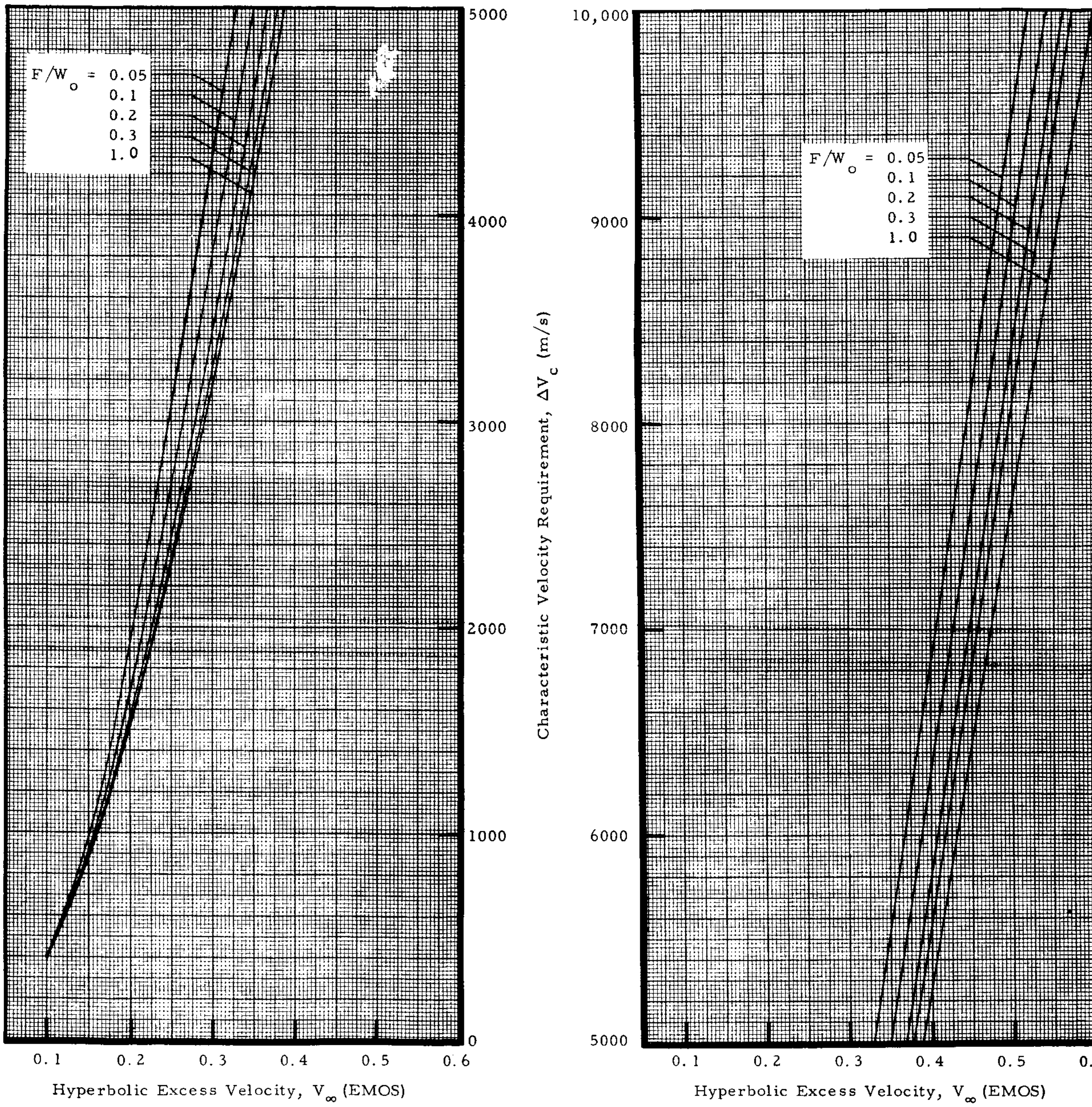


FIGURE 9a. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 800 s
$(V_e)_{max}$ = 11030 m/s

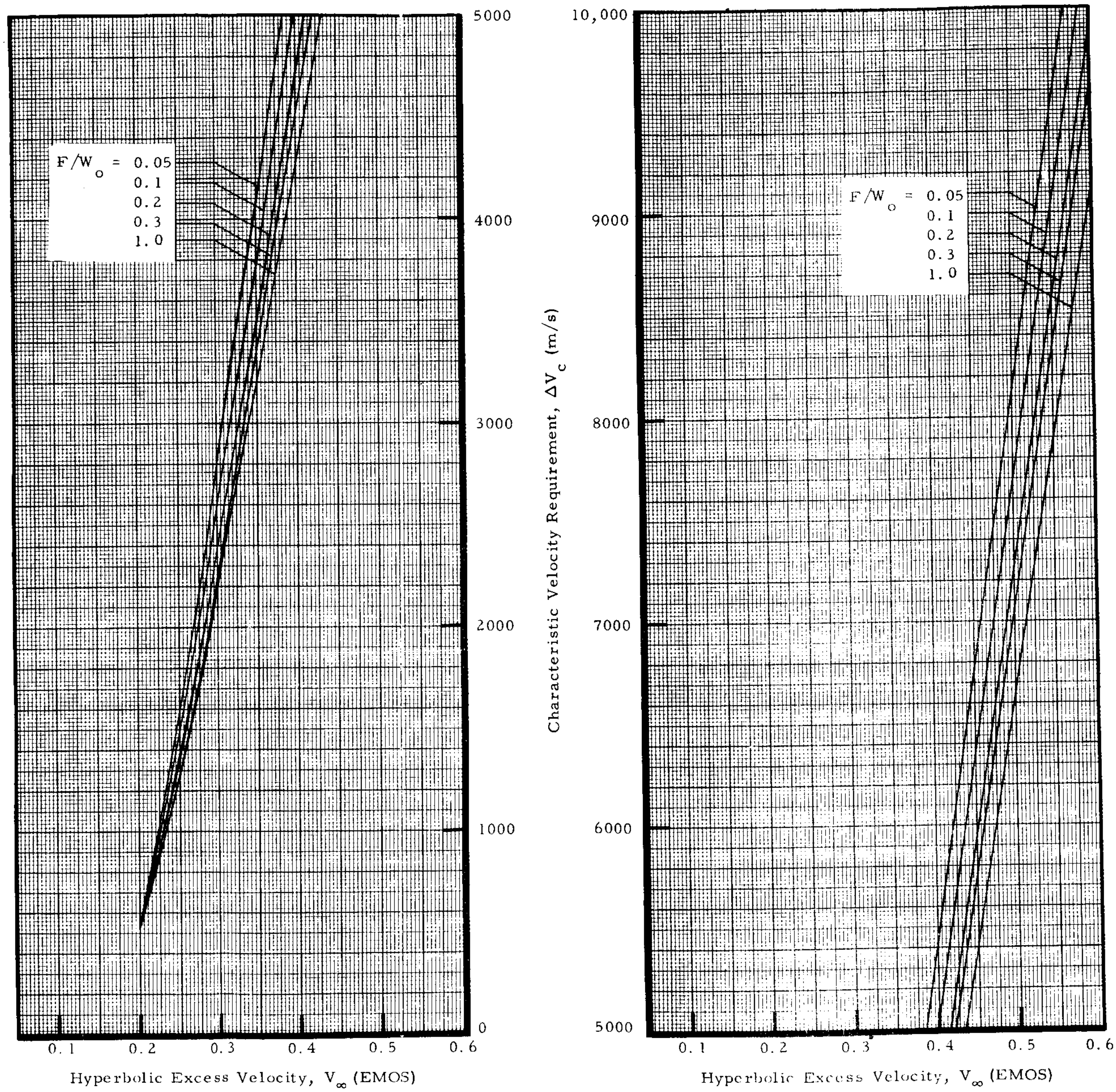


FIGURE 9b. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 800 s
$(V_e)_{max}$ = 12000 m/s

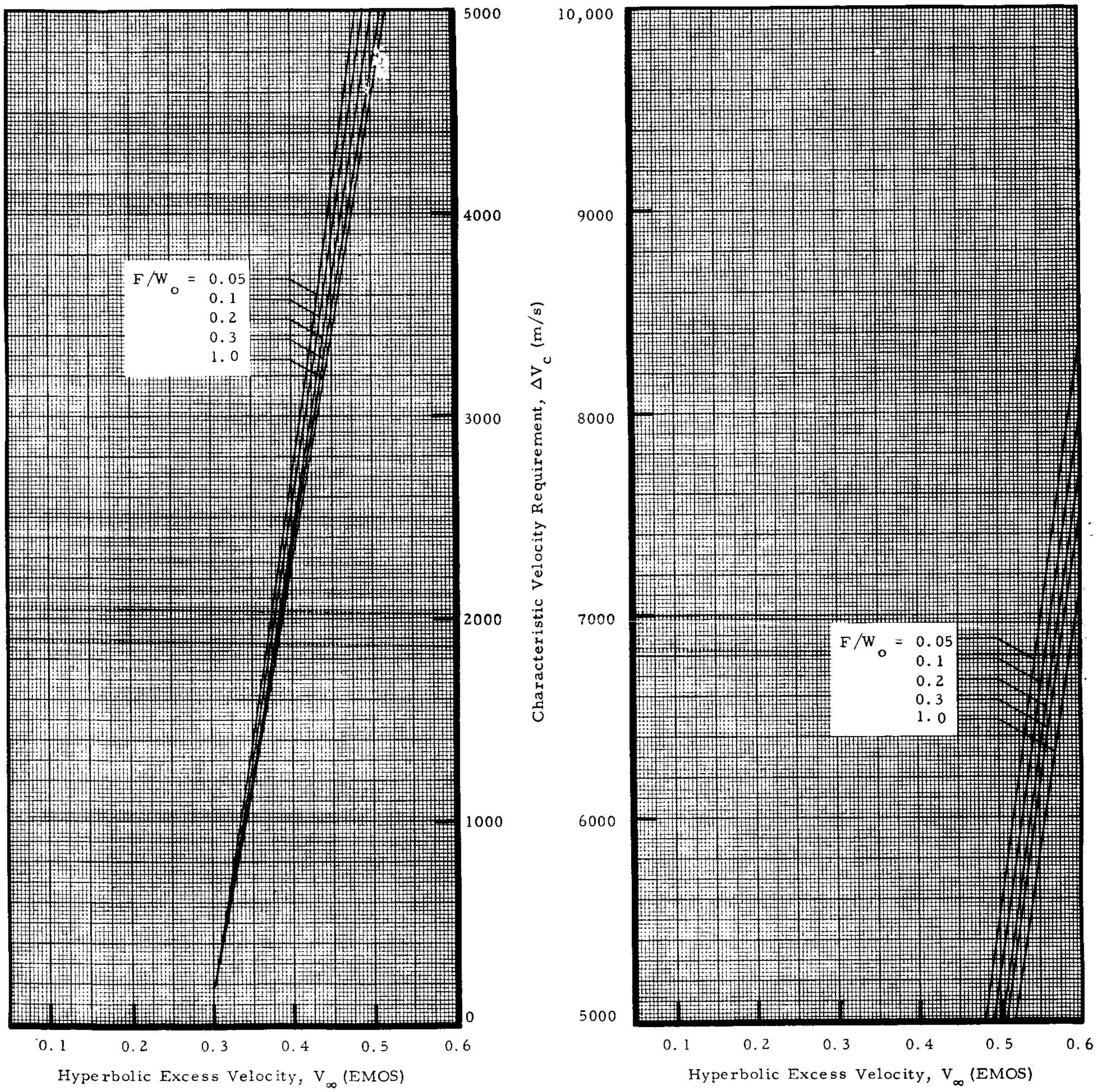


FIGURE 9c. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 800 s
$(V_e)_{max}$ = 14000 m/s

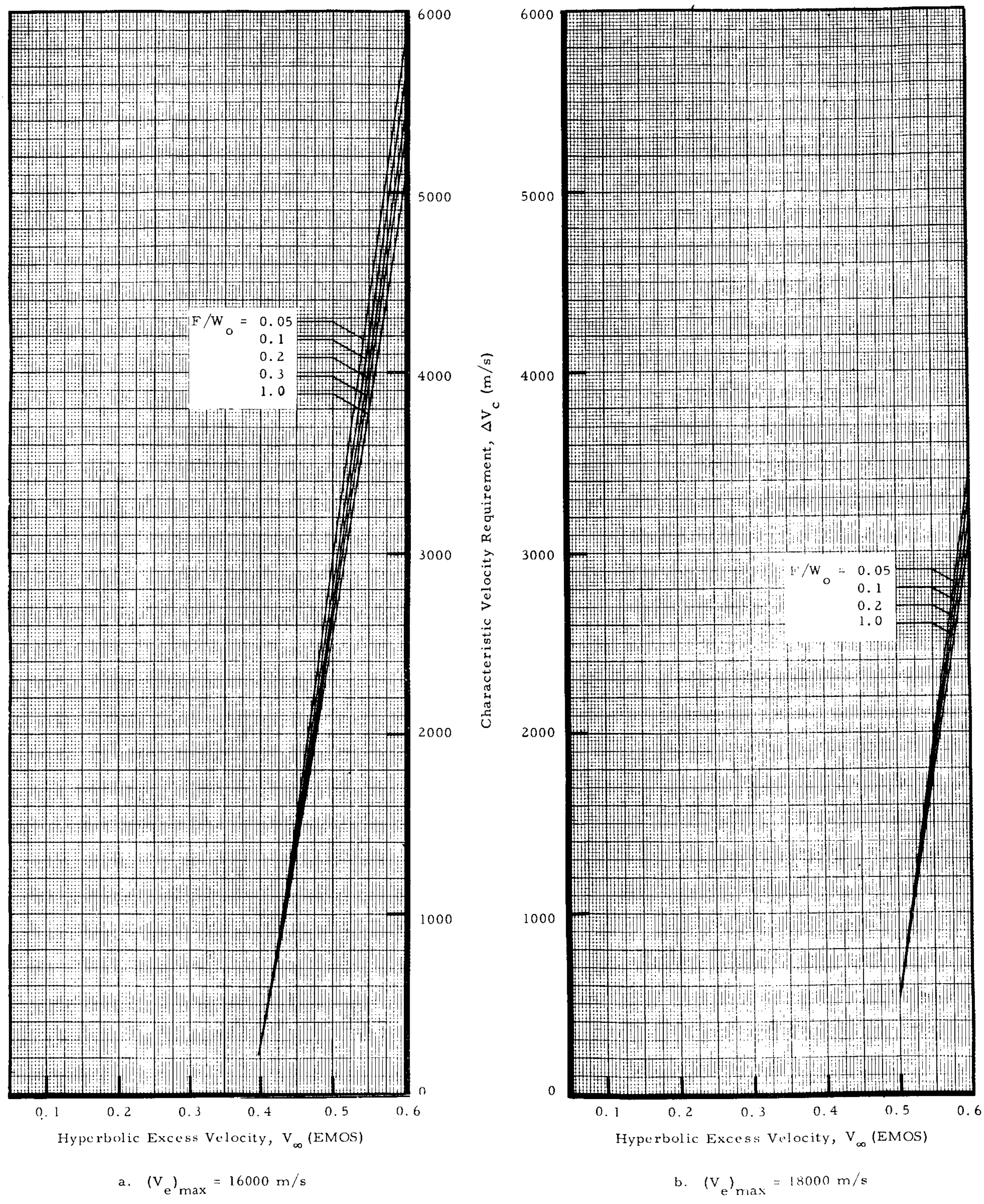


FIGURE 9d. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 800 s

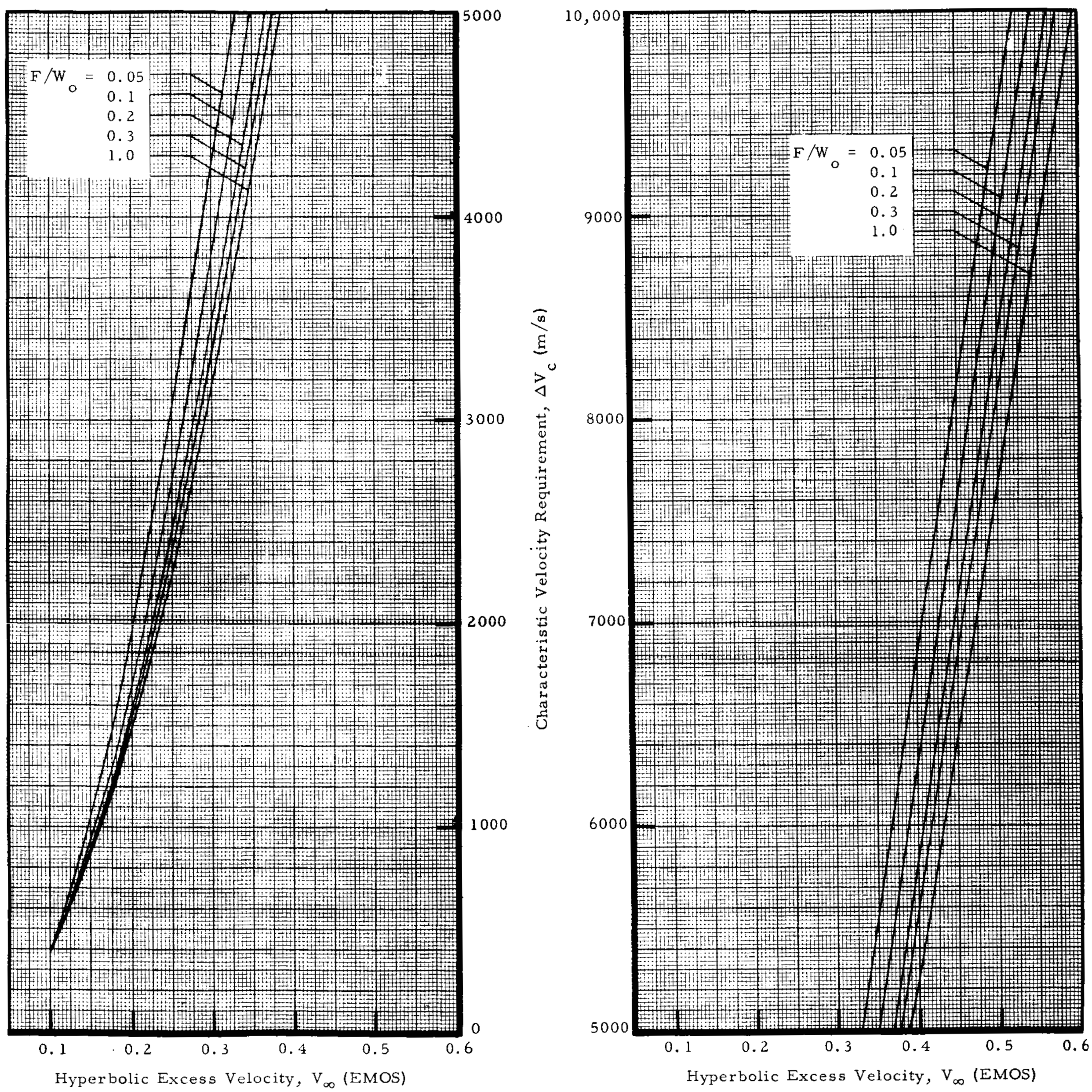


FIGURE 10a. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 825 s
$(V_e)_{max}$ = 11030 m/s

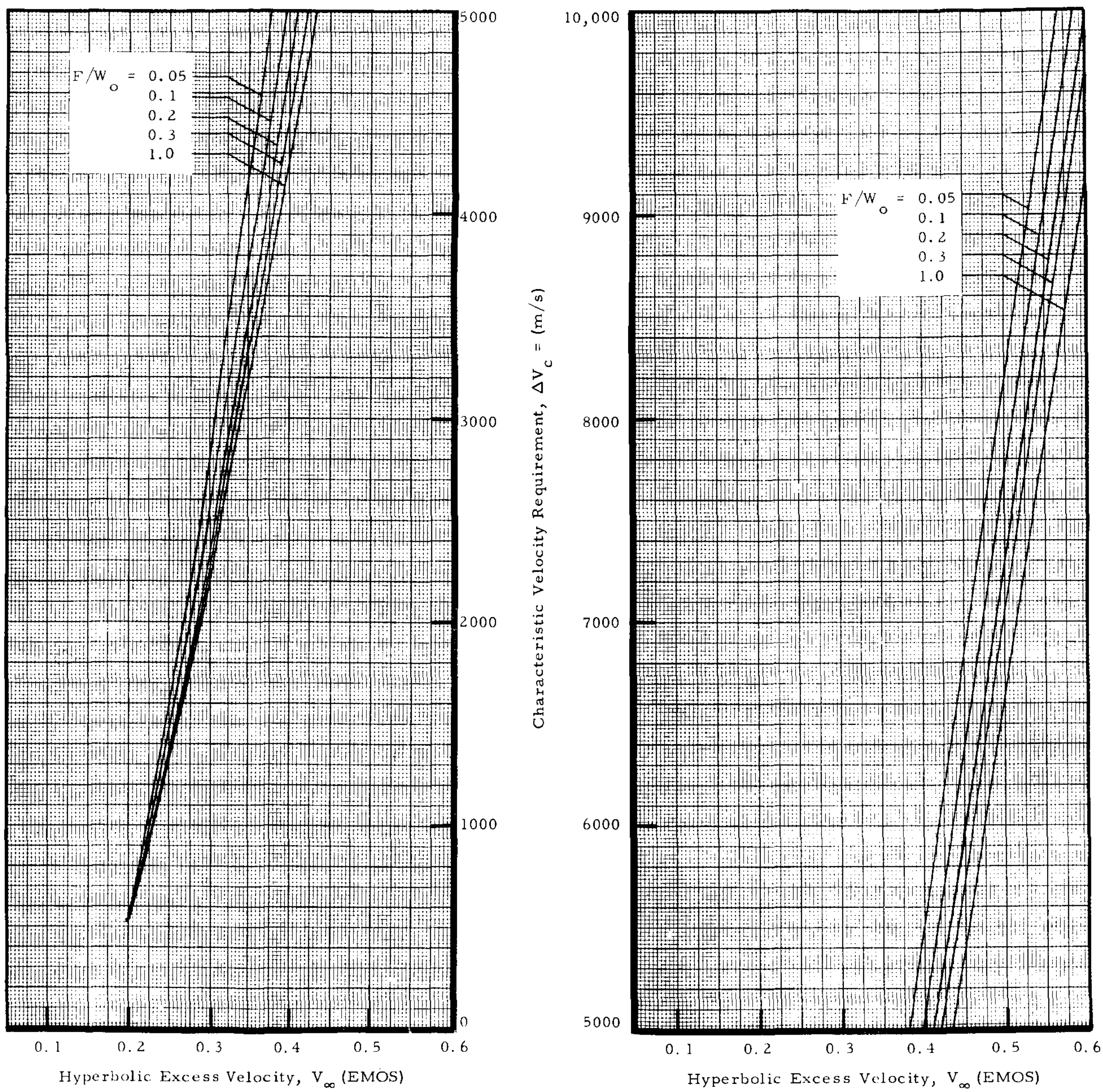


FIGURE 10b. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR $I_{sp} = 825$ s
$(V_e)_{max} = 12000$ m/s

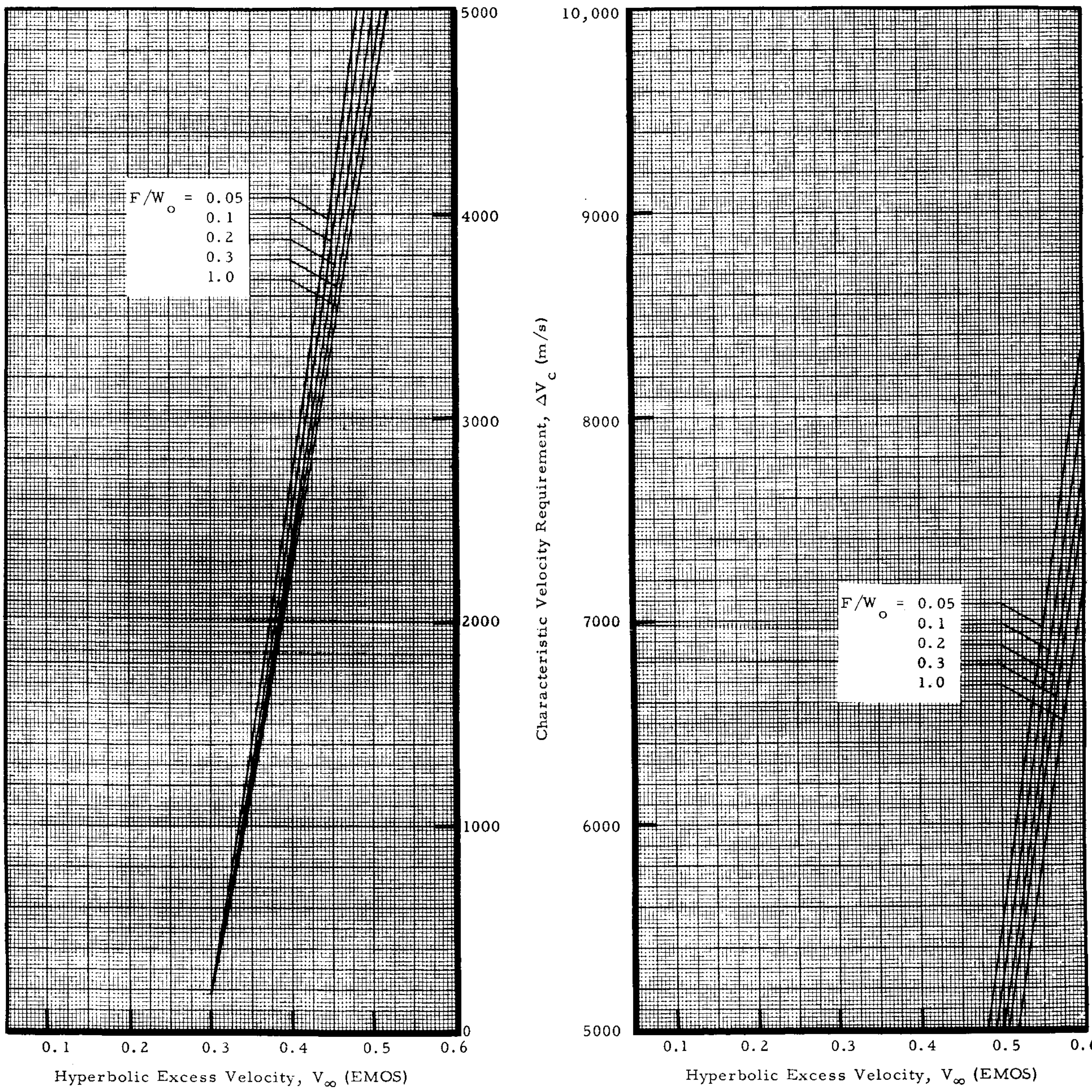


FIGURE 10c. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 825 s
$(V_e)_{max}$ = 14000 m/s

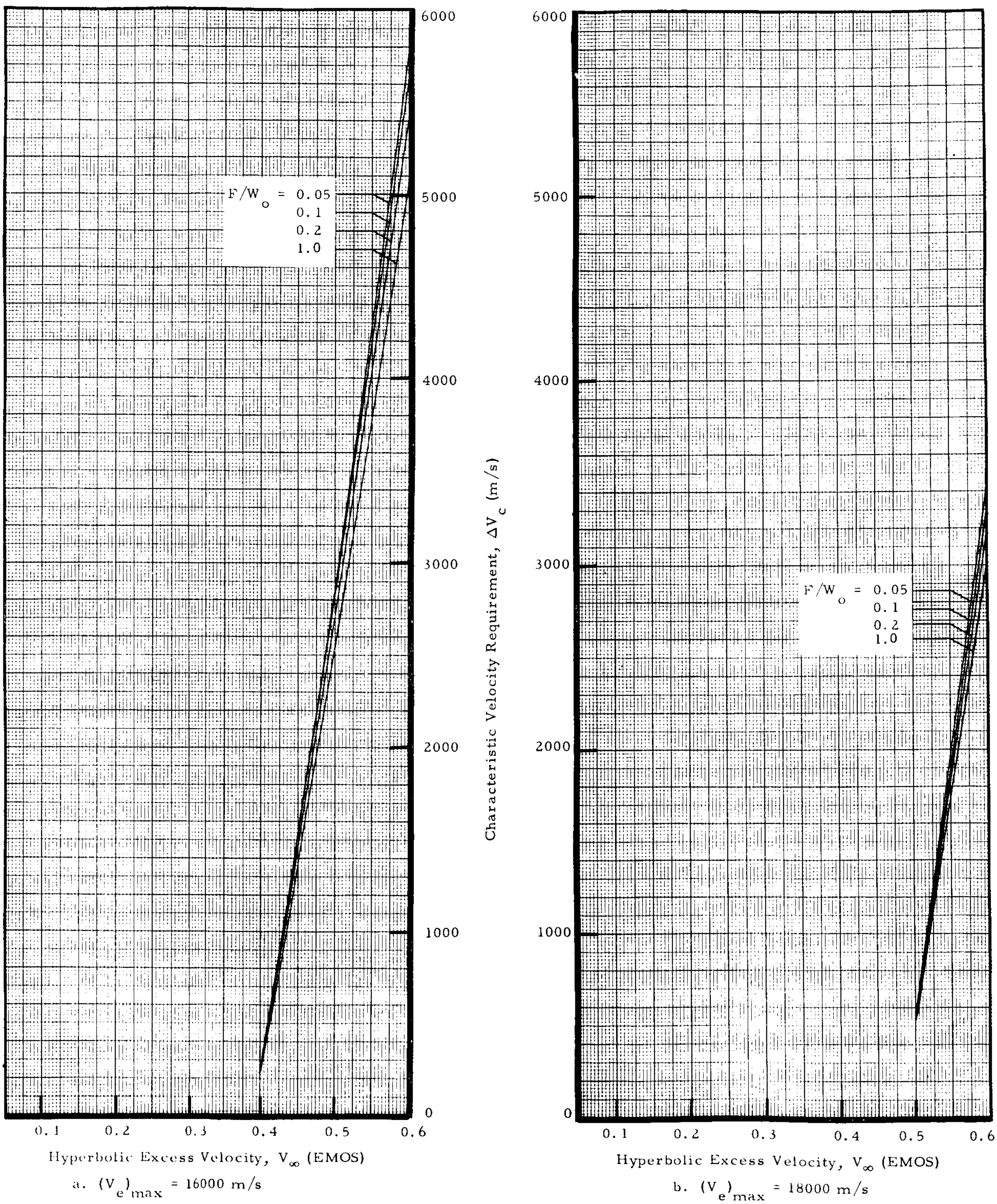


FIGURE 10d. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR I_{sp} = 825 s

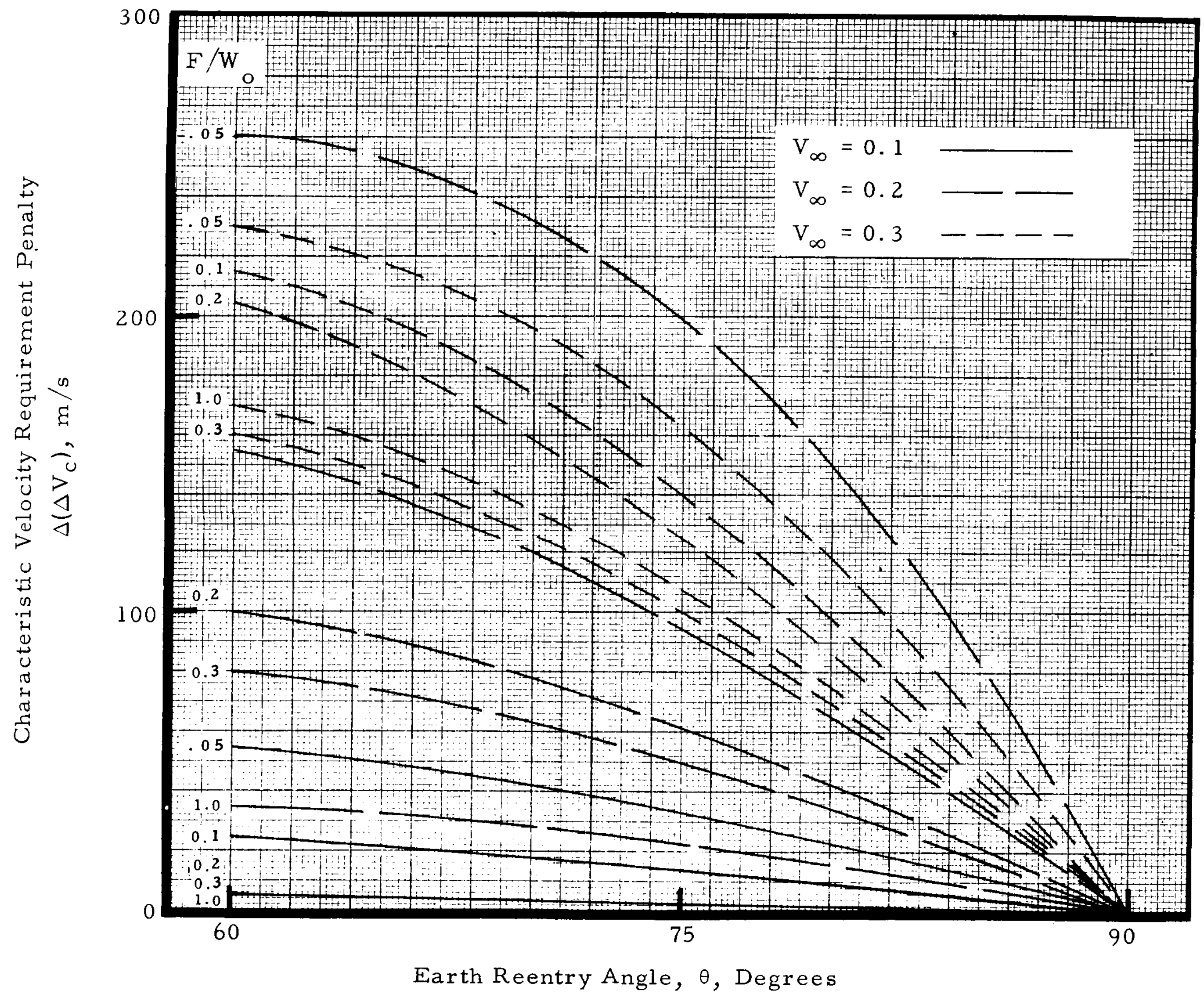


FIGURE 11a. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR $\theta_{REF} = 90°$

I_{sp} = 330 sec $(V_e)_{max}$ = 11030 m/s

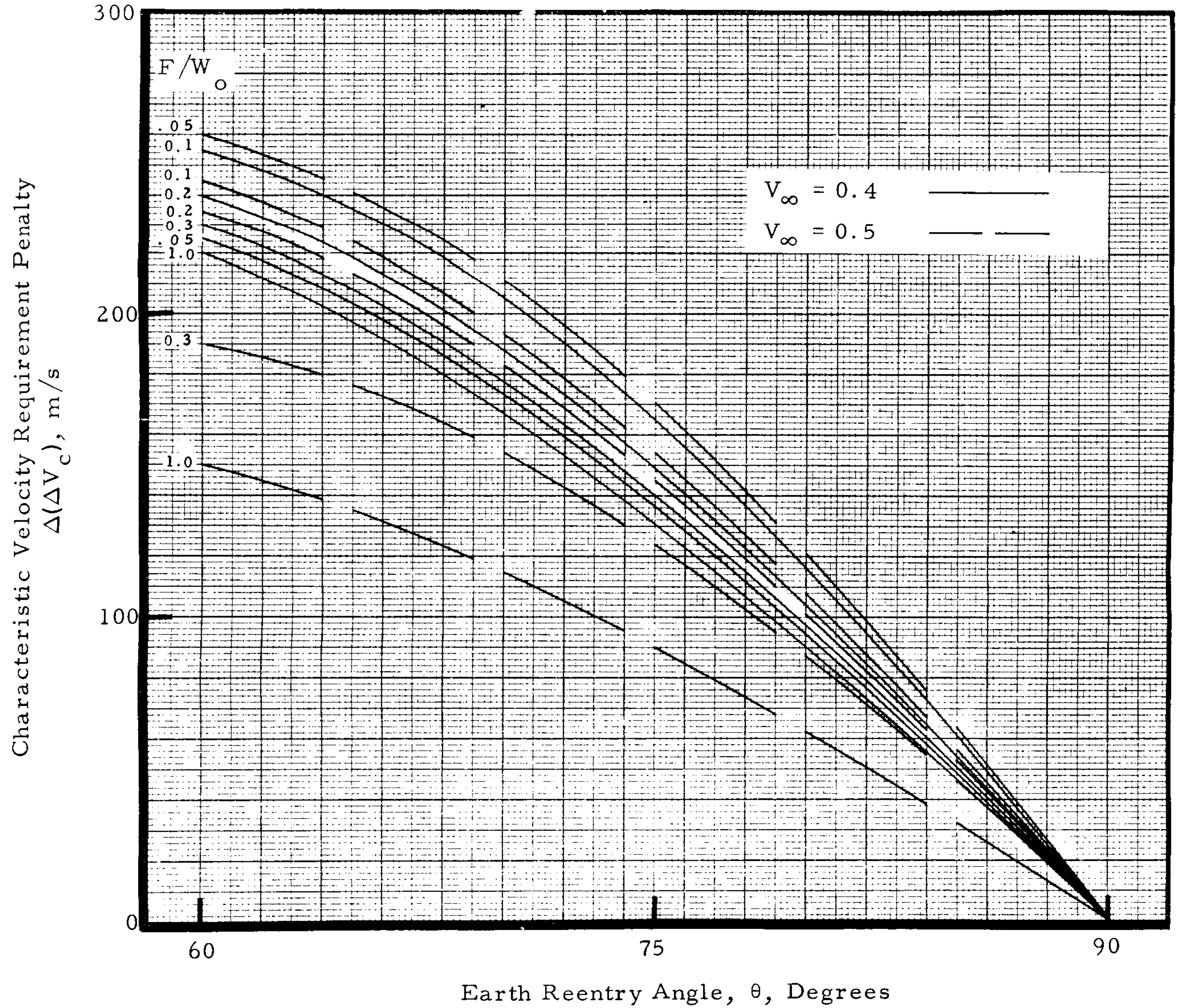


FIGURE 11b. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR $\theta_{REF} = 90°$

I_{sp} = 330 sec $(V_e)_{max}$ = 11030 m/s

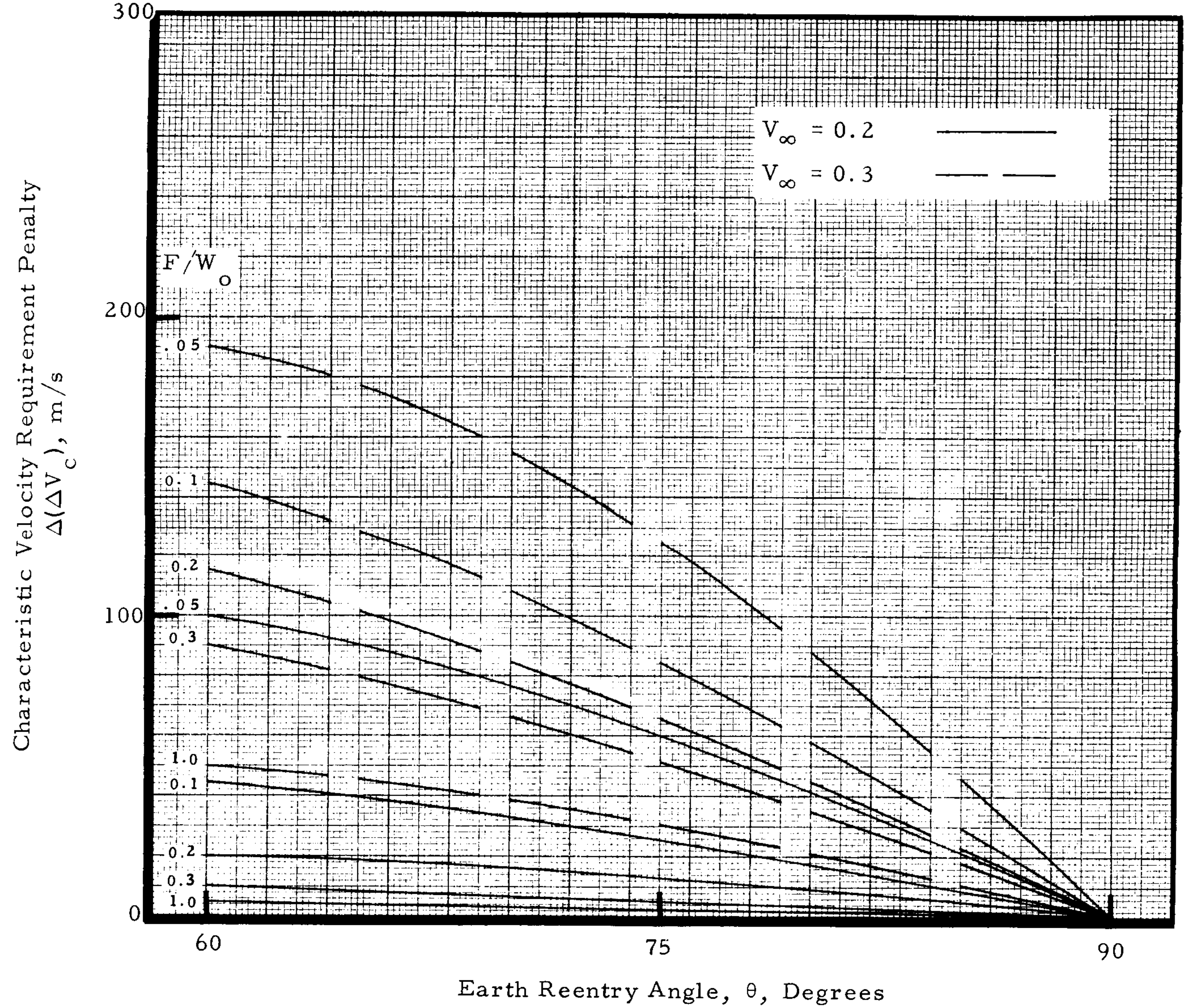


FIGURE 12a. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR $\theta_{REF} = 90°$

I_{sp} = 330 sec $(V_e)_{max}$ = 12000 m/s

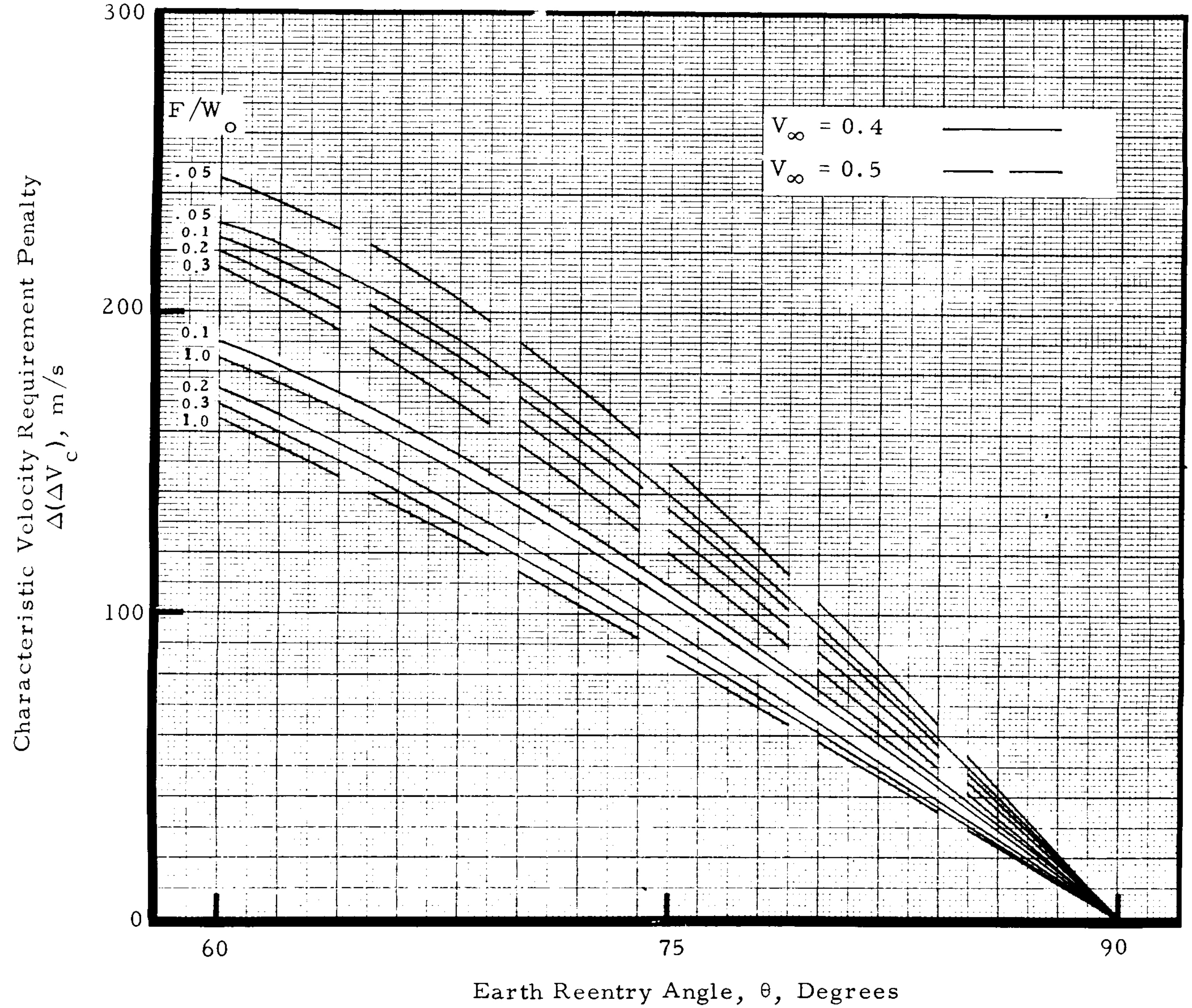


FIGURE 12b. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR θ_{REF} = 90°

I_{sp} = 330 sec $(V_e)_{max}$ = 12000 m/s

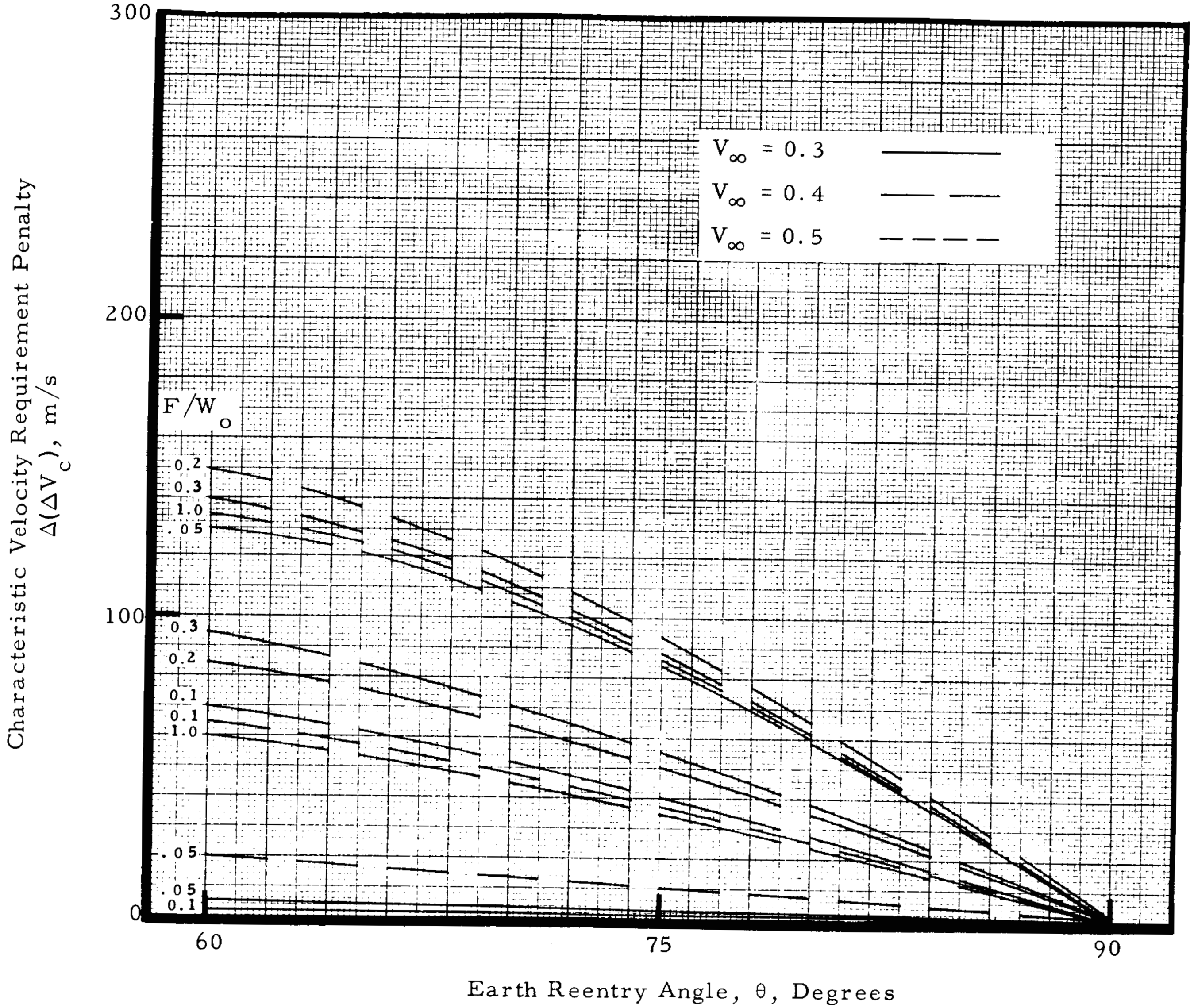


FIGURE 13. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR $\theta_{REF} = 90°$

$I_{sp} = 330$ sec $\qquad (V_e)_{max} = 14000$ m/s

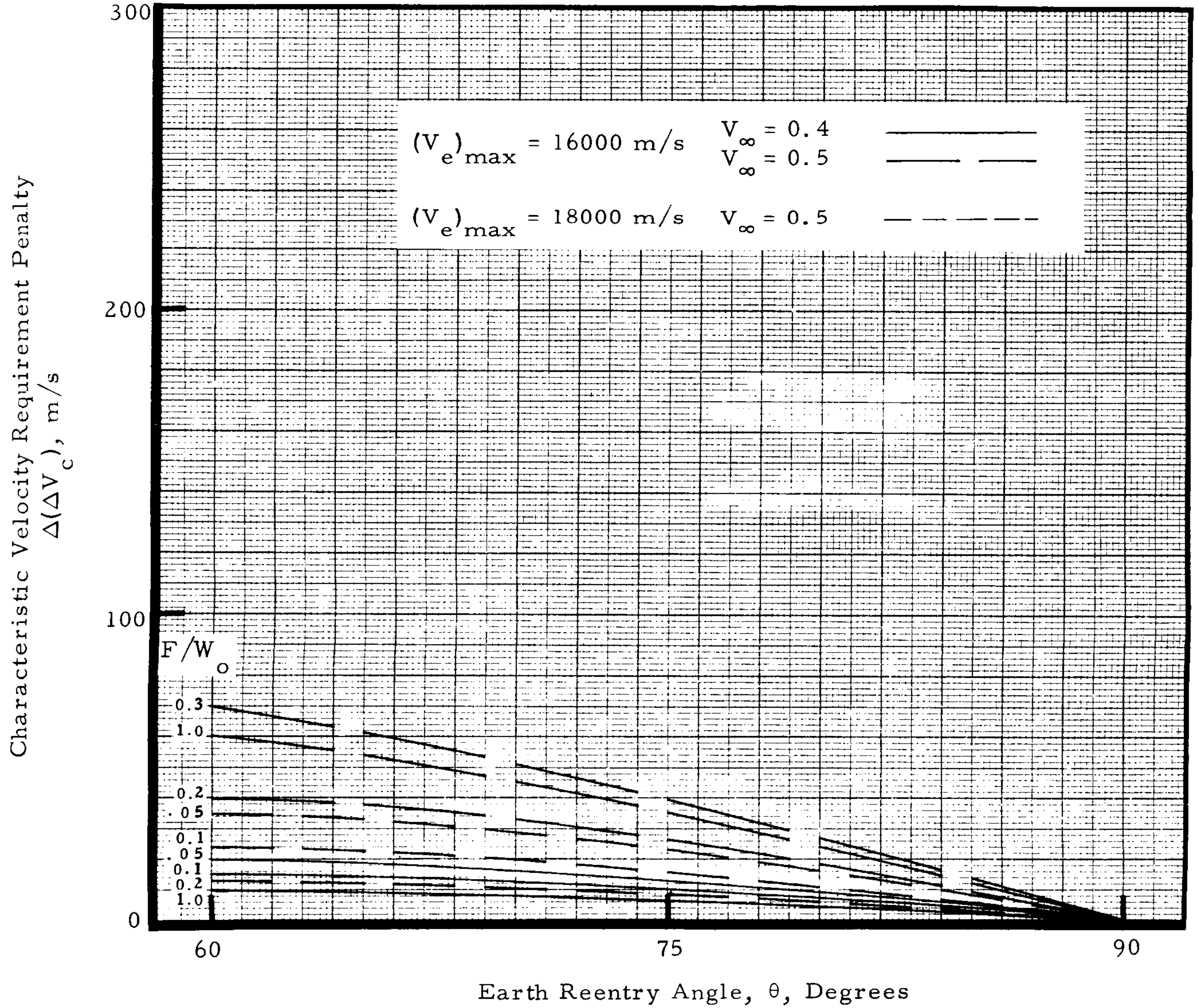


FIGURE 14. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR $\theta_{REF} = 90°$

I_{sp} = 330 sec $(V_e)_{max}$ = 16000 - 18000 m/s

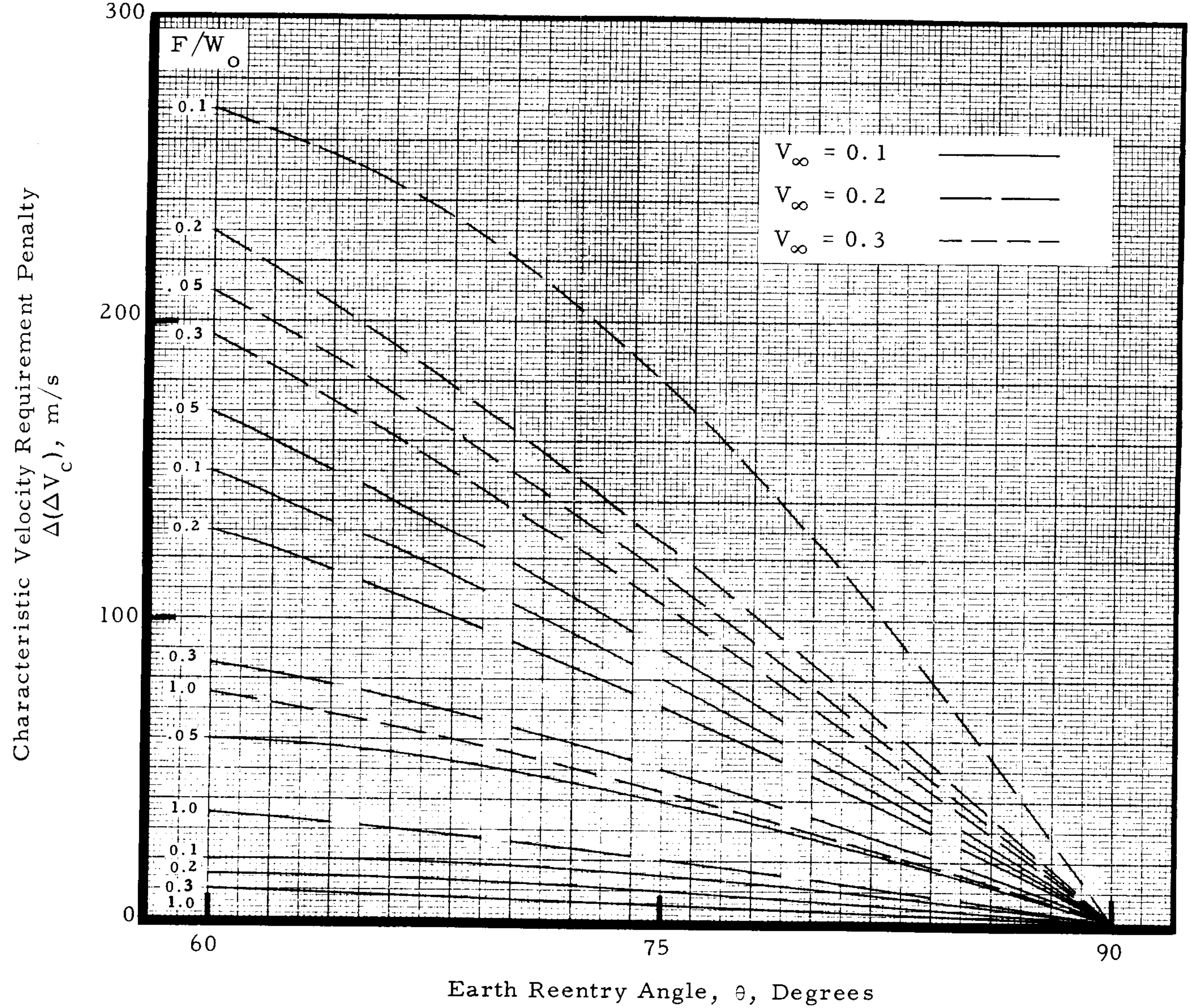


FIGURE 15a. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR $\theta_{REF} = 90°$

$I_{sp} = 430$ sec $(V_e)_{max} = 11030$ m/s

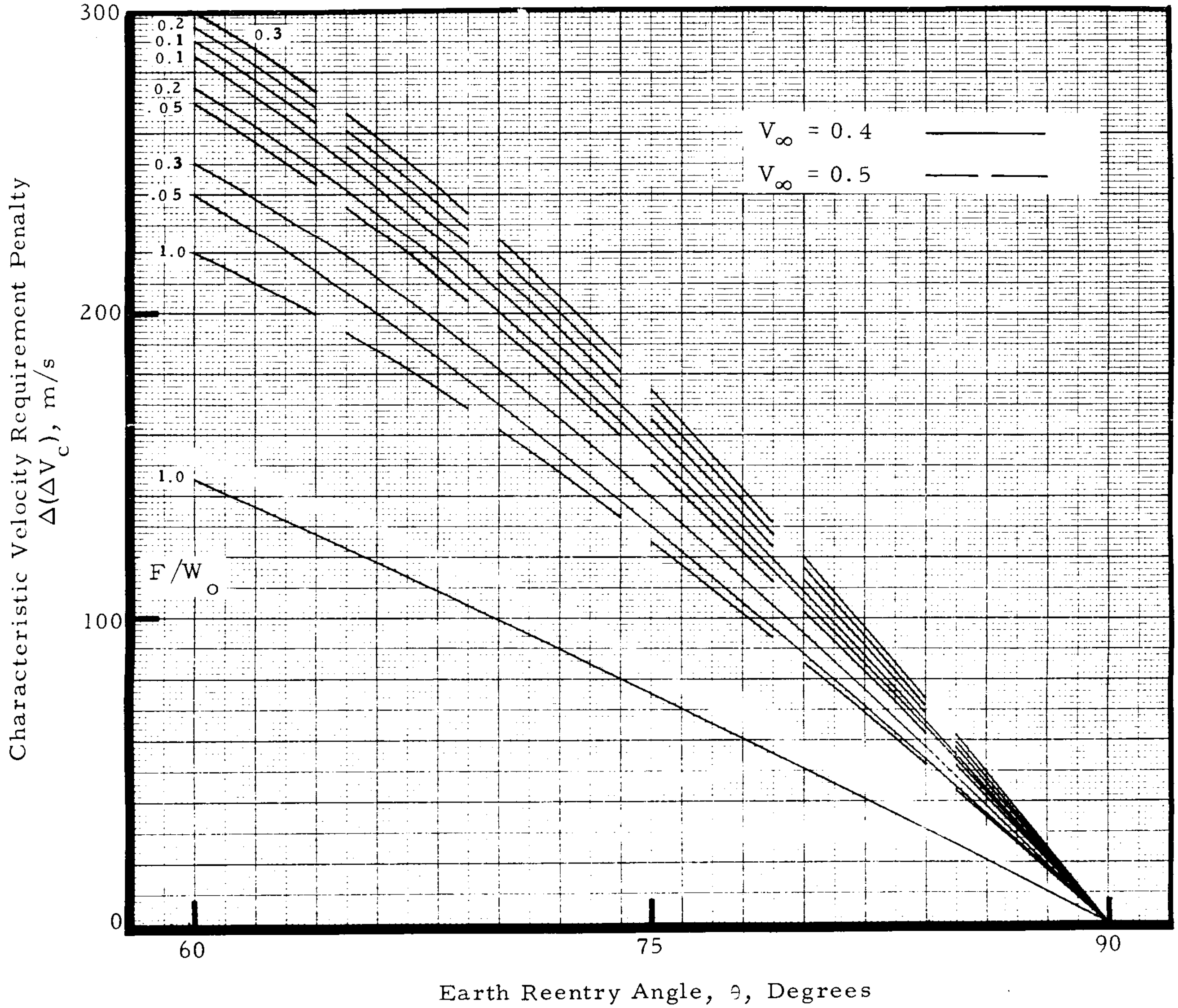


FIGURE 15b. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR $\theta_{REF} = 90°$

I_{sp} = 430 sec $(V_e)_{max}$ = 11030 m/s

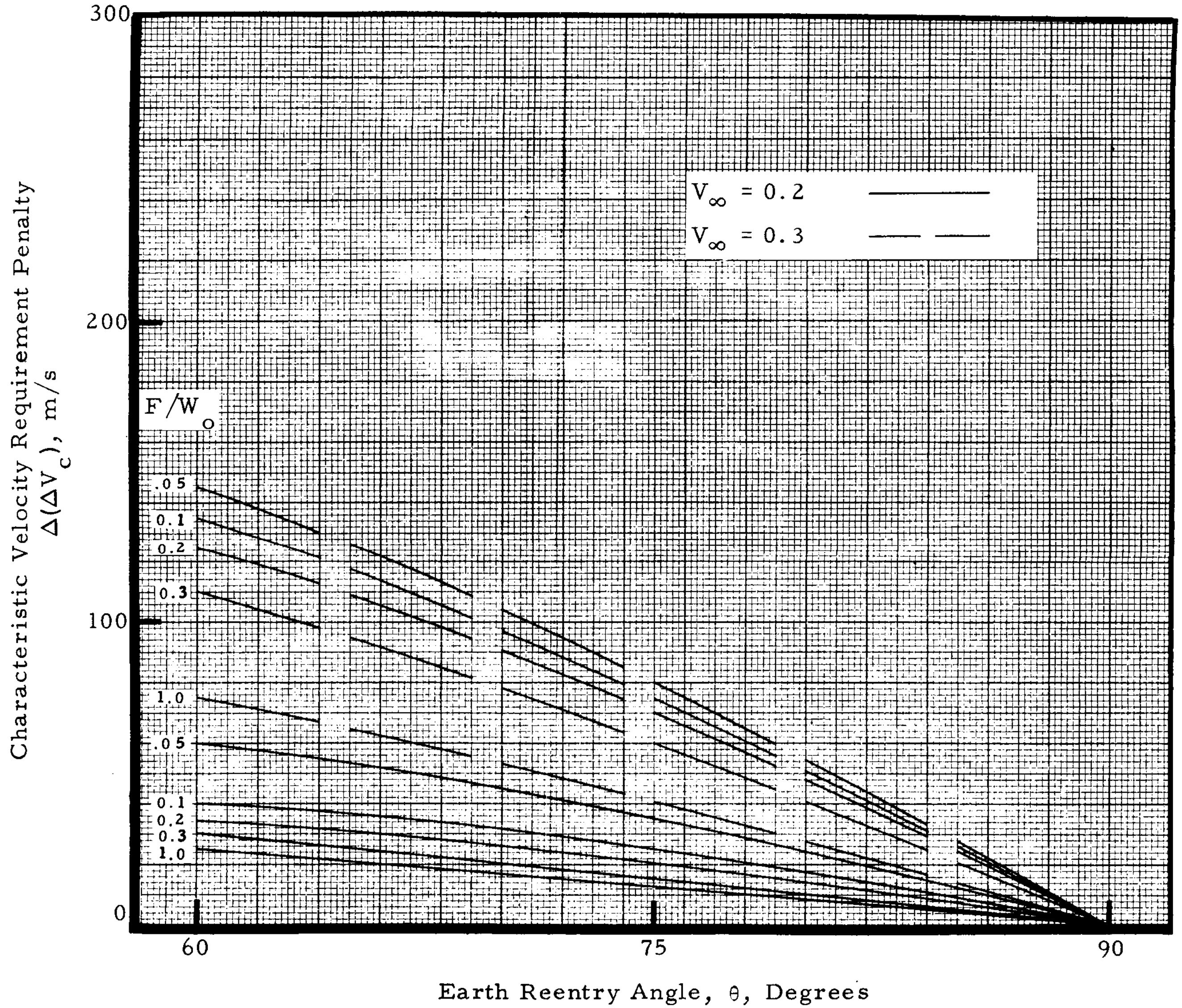


FIGURE 16a. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR $\theta_{REF} = 90°$

$I_{sp} = 430$ sec $\quad\quad (V_e)_{max} = 12000$ m/s

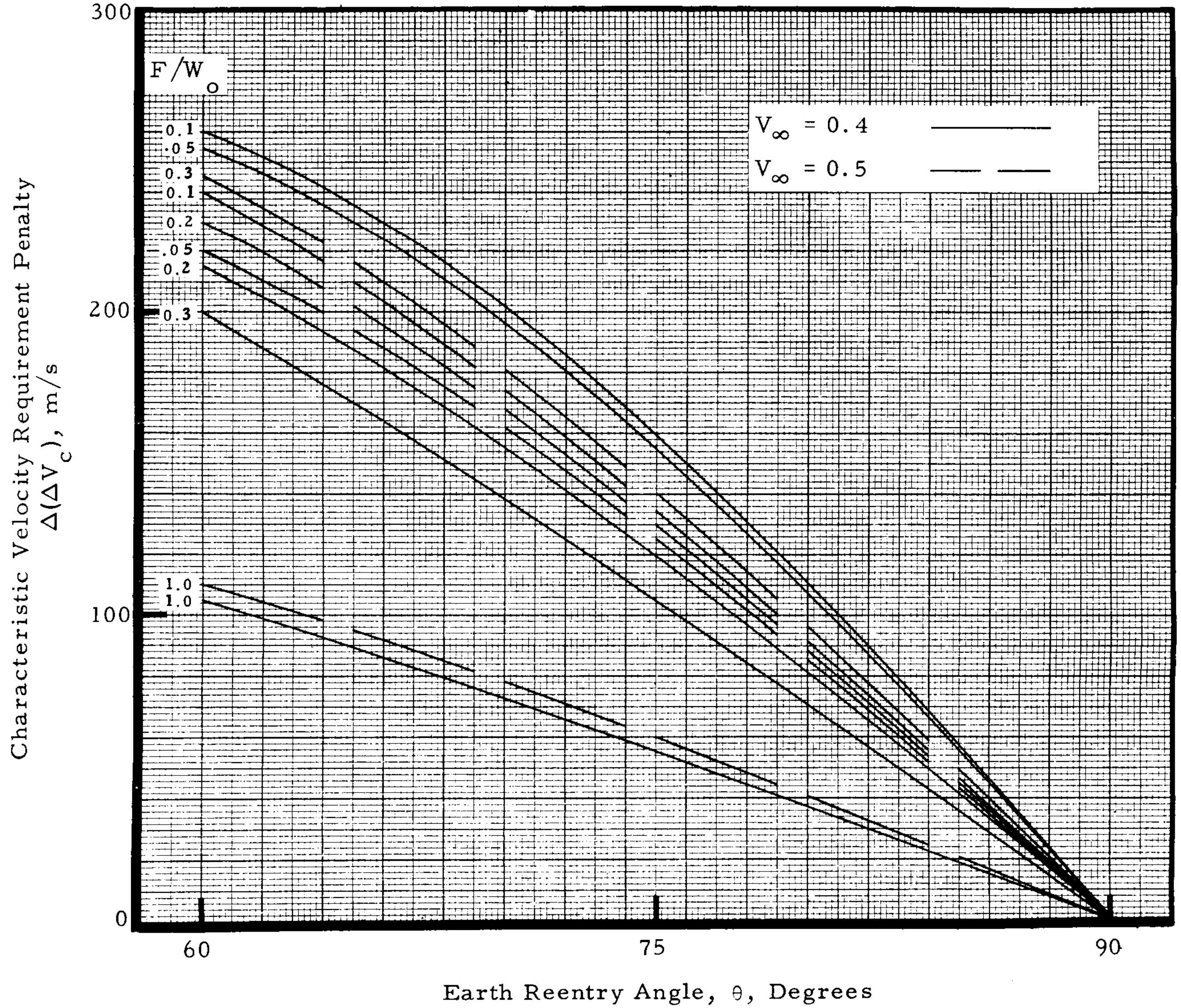


FIGURE 16b. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR $\theta_{REF} = 90°$

$I_{sp} = 430$ sec $\qquad (V_e)_{max} = 12000$ m/s

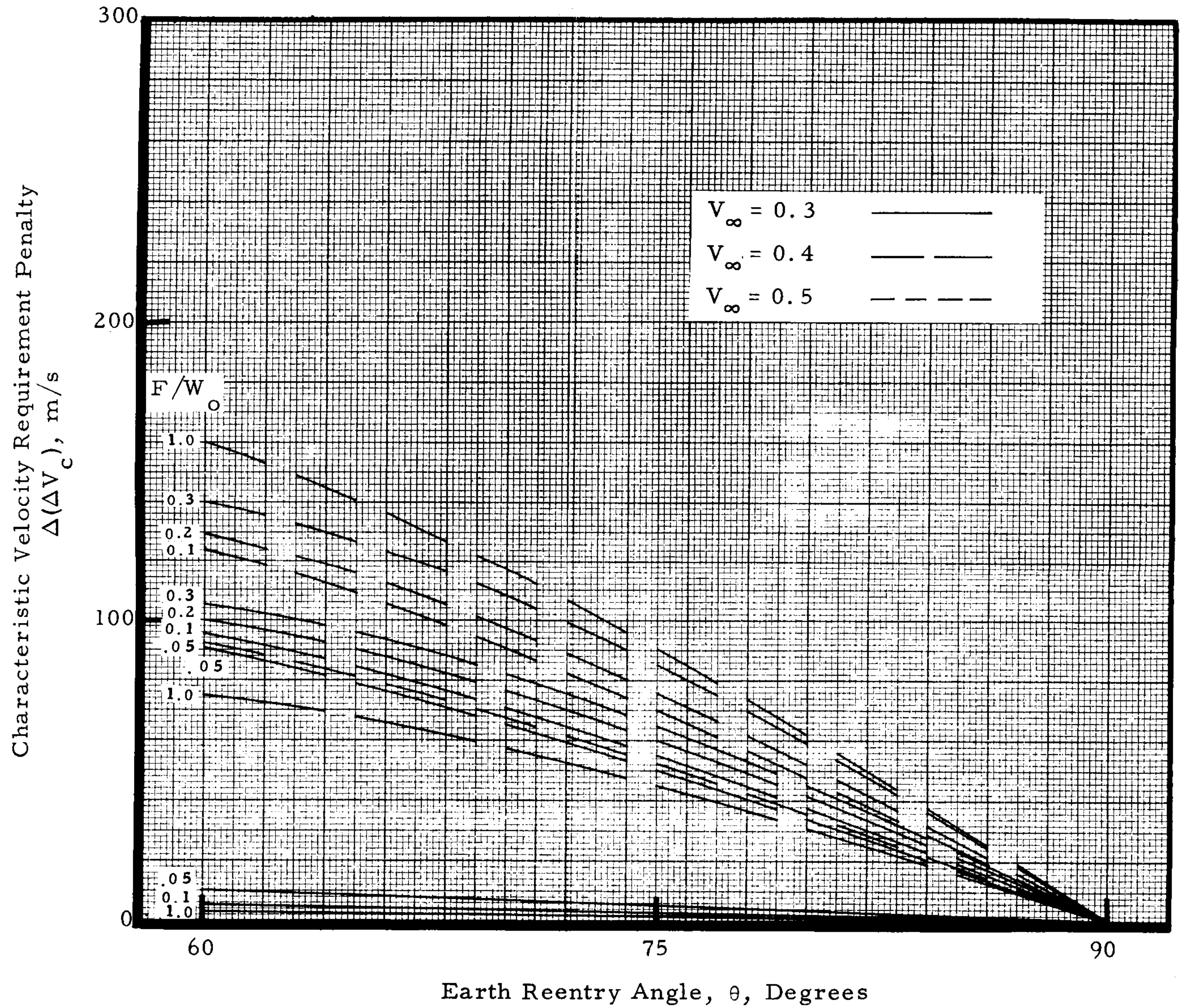


FIGURE 17 CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR $\theta_{REF} = 90°$

$I_{sp} = 430$ sec $(V_e)_{max} = 14000$ m/s

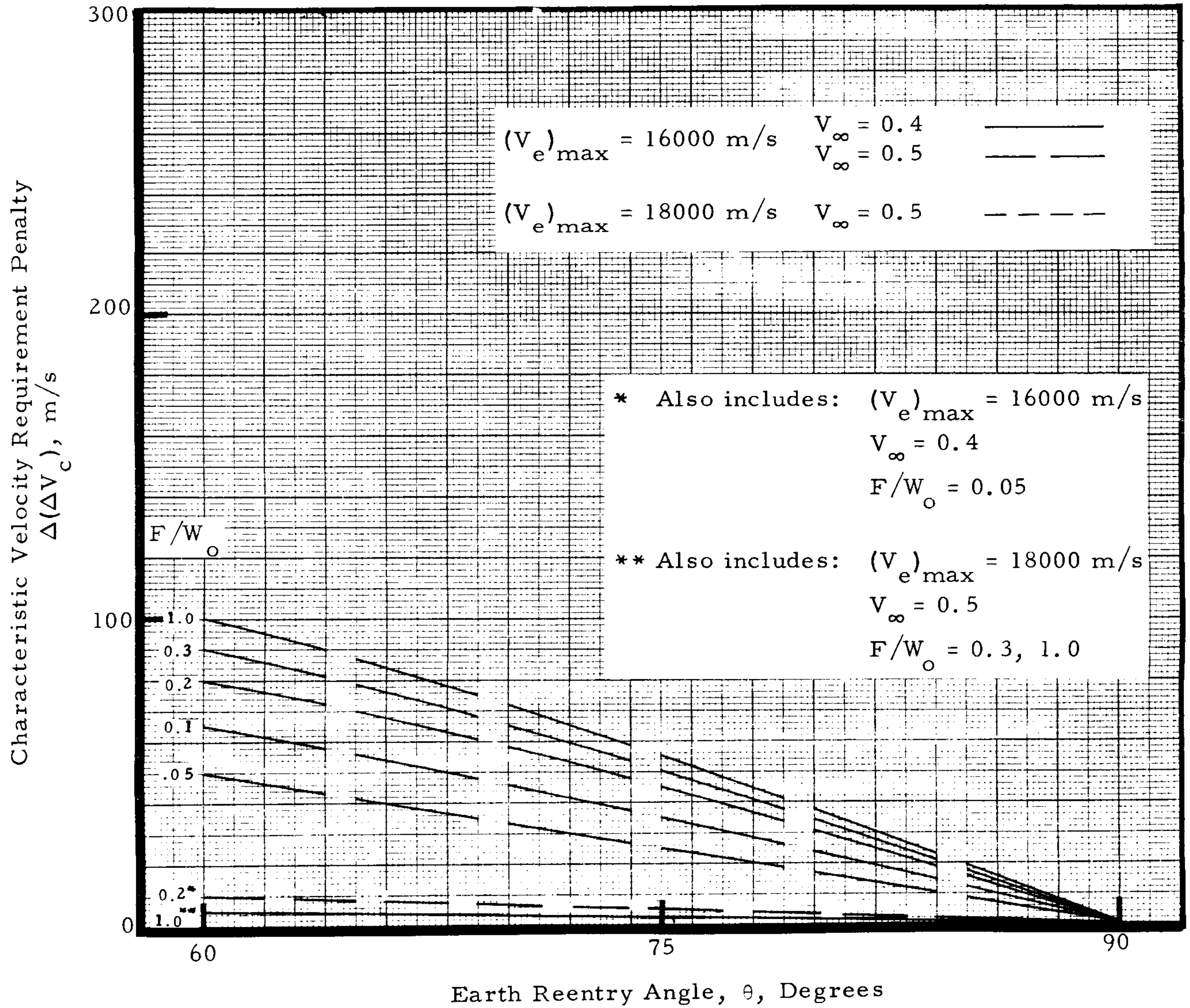


FIGURE 18. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR $\theta_{REF} = 90°$

$I_{sp} = 430$ sec $(V_e)_{max} = 16000\text{-}18000$ m/s

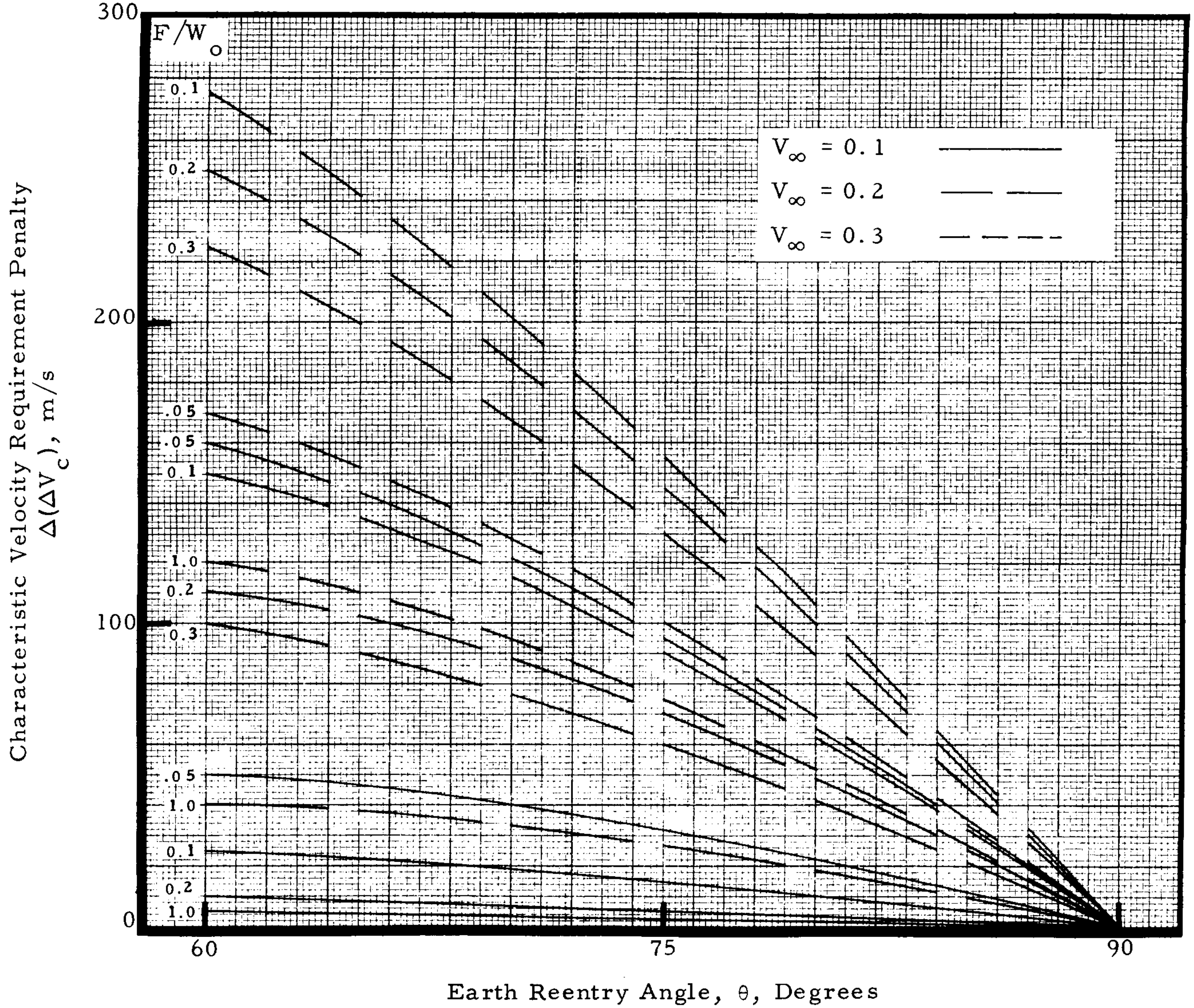


FIGURE 19a. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR $\theta_{REF} = 90°$

I_{sp} = 800 sec $(V_e)_{max}$ = 11030 m/s

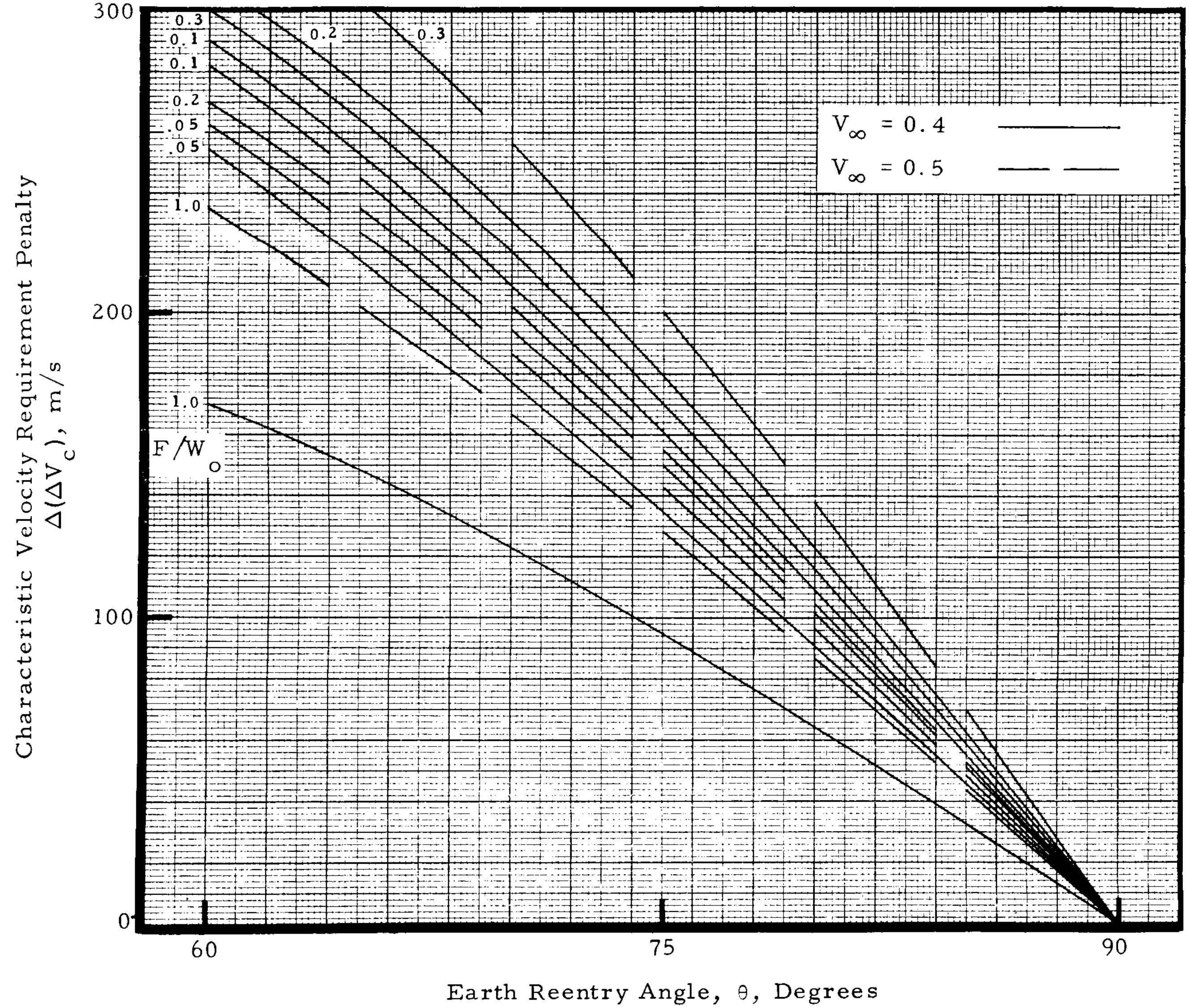


FIGURE 19b. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR $\theta_{REF} = 90°$

I_{sp} = 800 sec $(V_e)_{max}$ = 11030 m/s

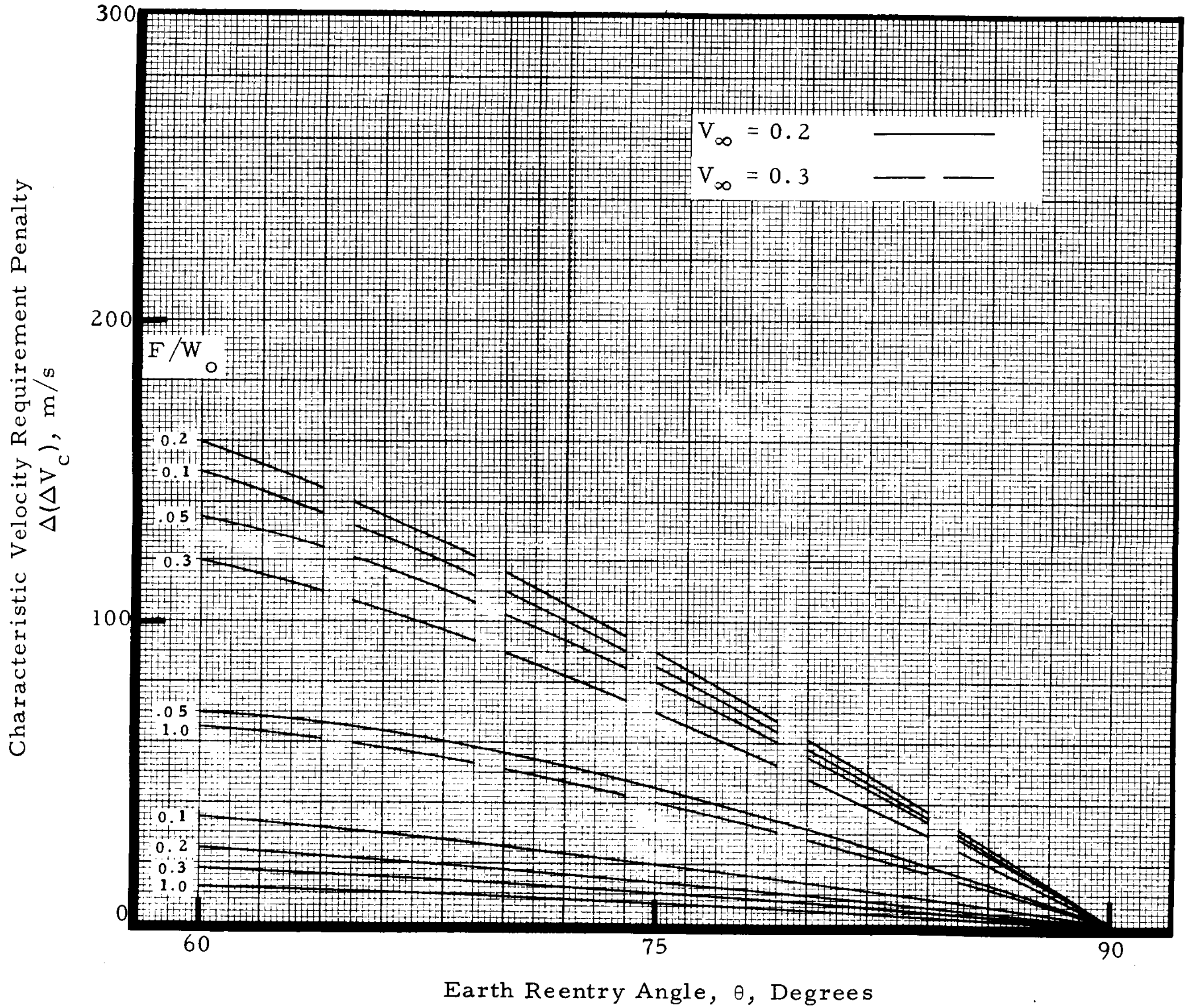


FIGURE 20a. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR θ_{REF} = 90°

I_{sp} = 800 sec $(V_e)_{max}$ = 12000 m/s

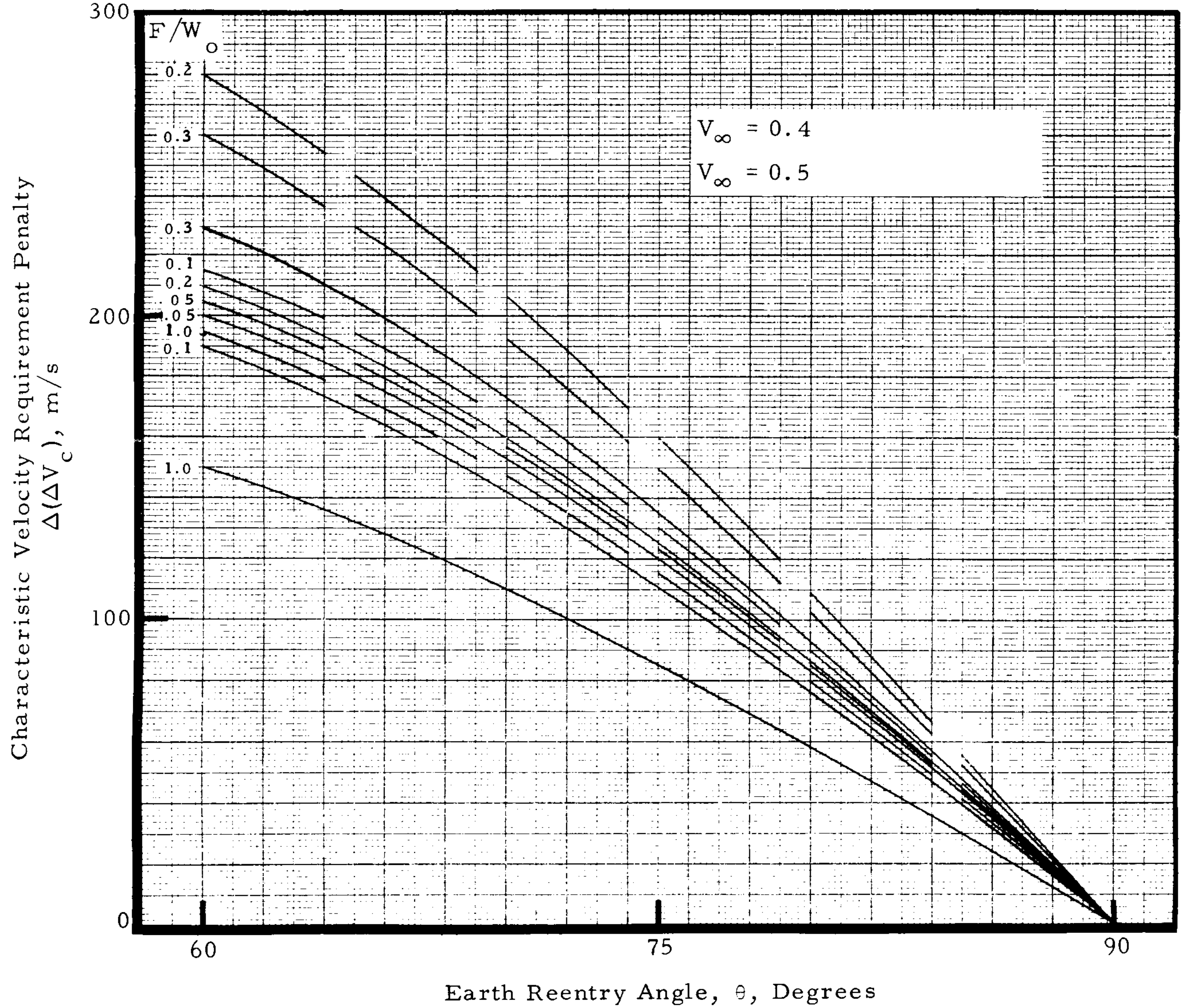


FIGURE 20b. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR $\theta_{REF} = 90°$

I_{sp} = 800 sec $(V_e)_{max}$ = 12000 m/s

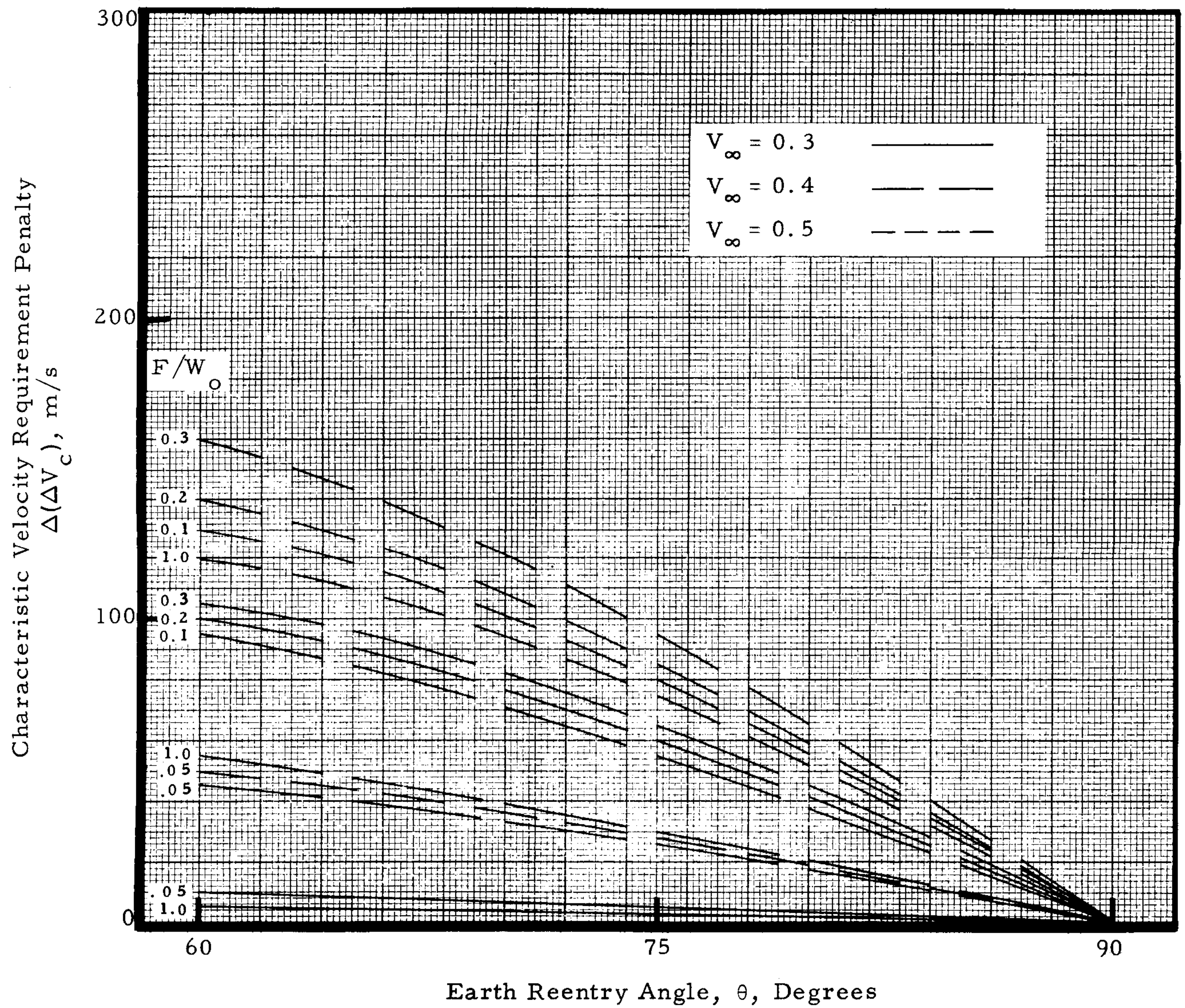


FIGURE 21. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR $\theta_{REF} = 90°$

$I_{sp} = 800$ sec $(V_e)_{max} = 14000$ m/s

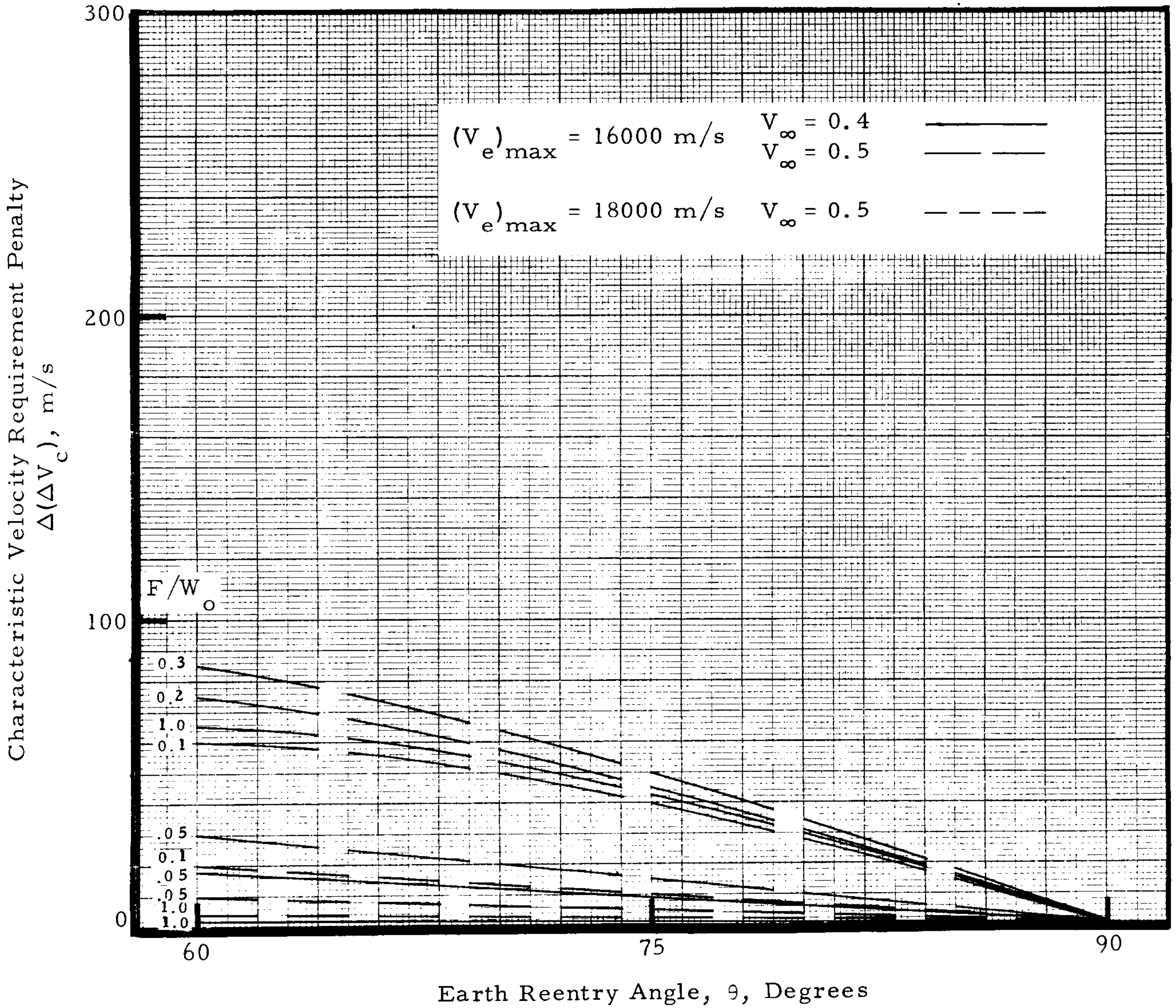


FIGURE 22 CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR θ_{REF} = 90°

I_{sp} = 800 sec $(V_e)_{max}$ = 16000-18000 m/s

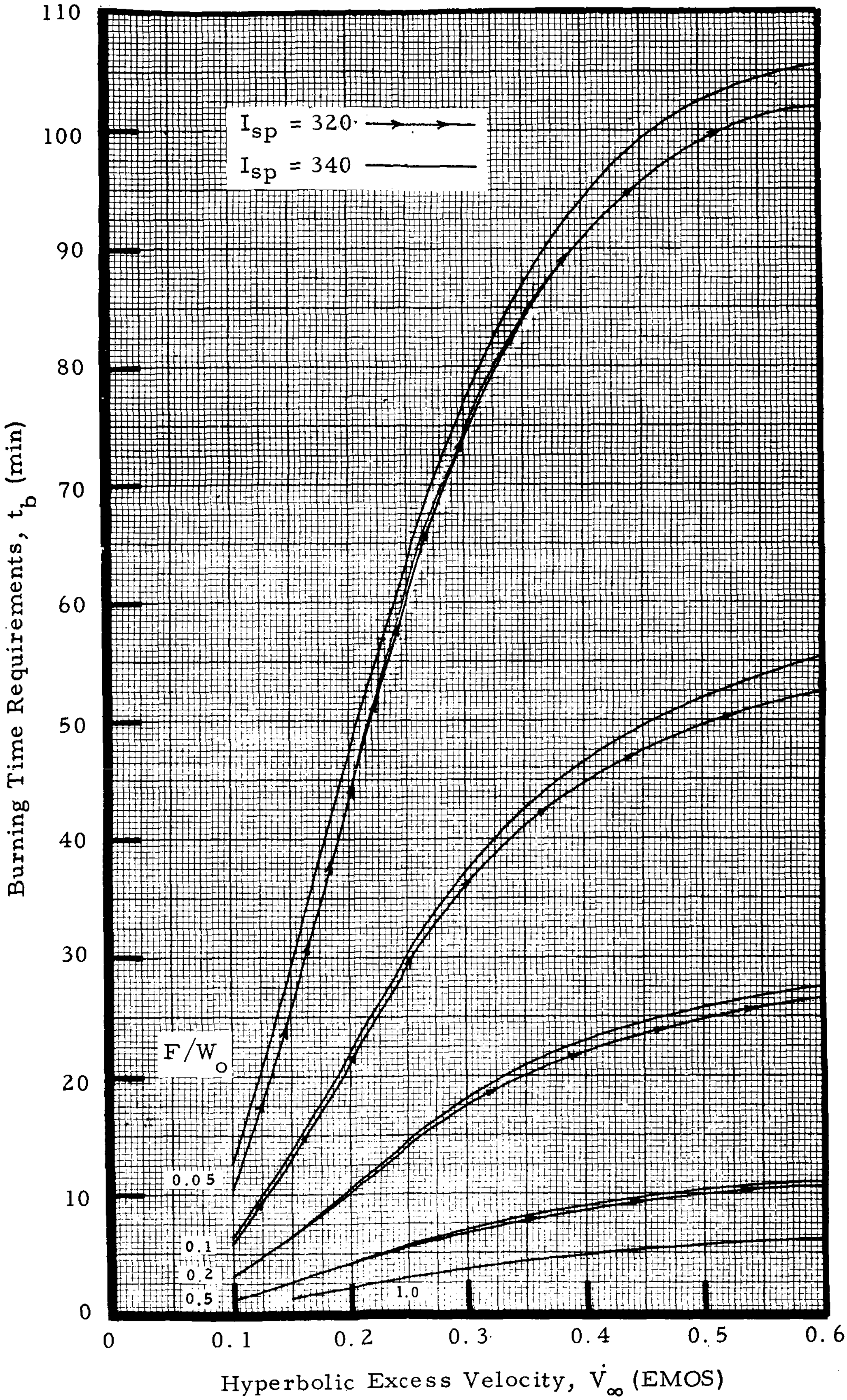


FIGURE 23a. BURNING TIME REQUIREMENTS FOR I_{sp} = 320 s AND 340 s, $(V_e)_{max}$ = 11030 m/s

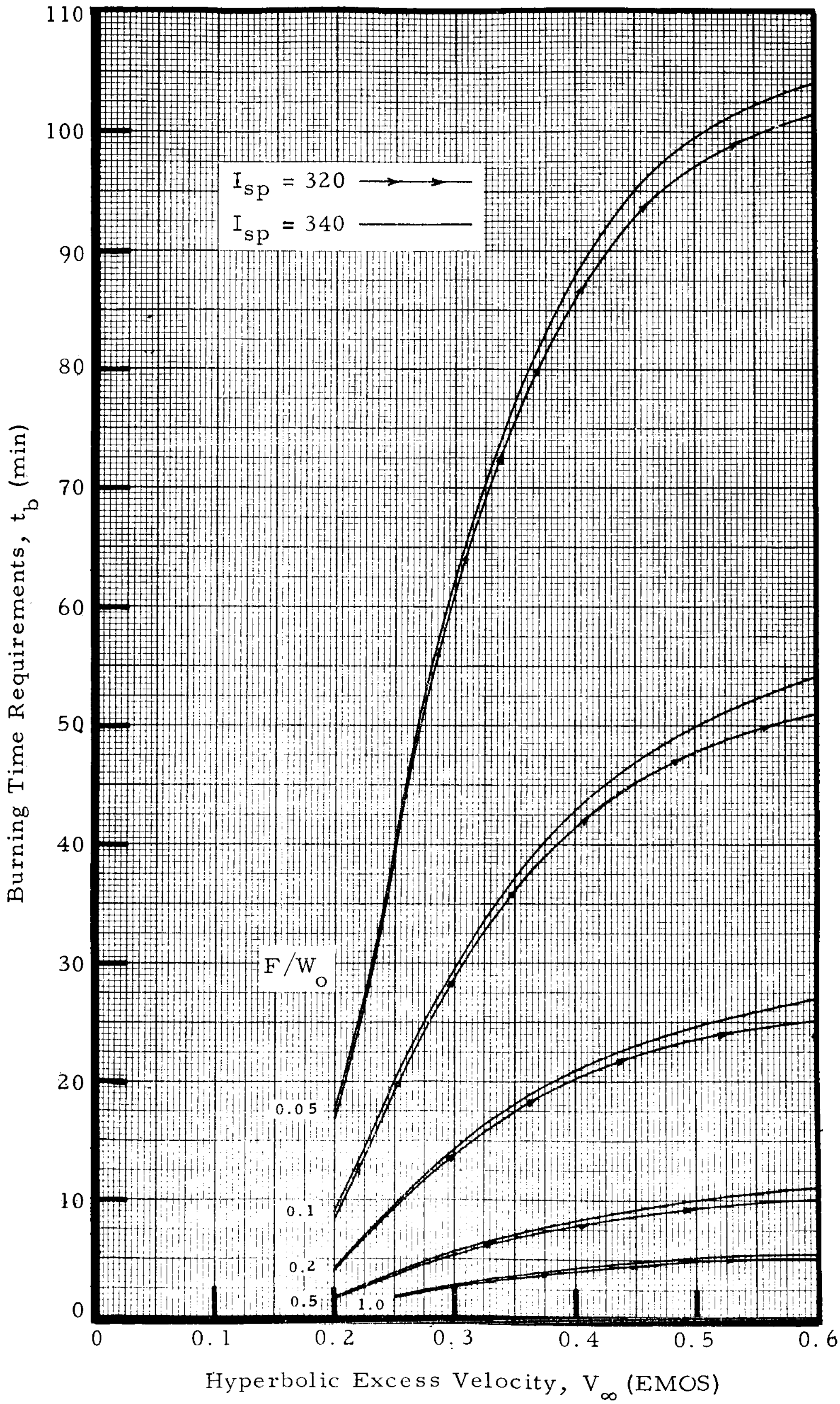


FIGURE 23b. BURNING TIME REQUIREMENTS FOR I_{sp} = 320 s AND 340 s, $(V_e)_{max}$ = 12000 m/s

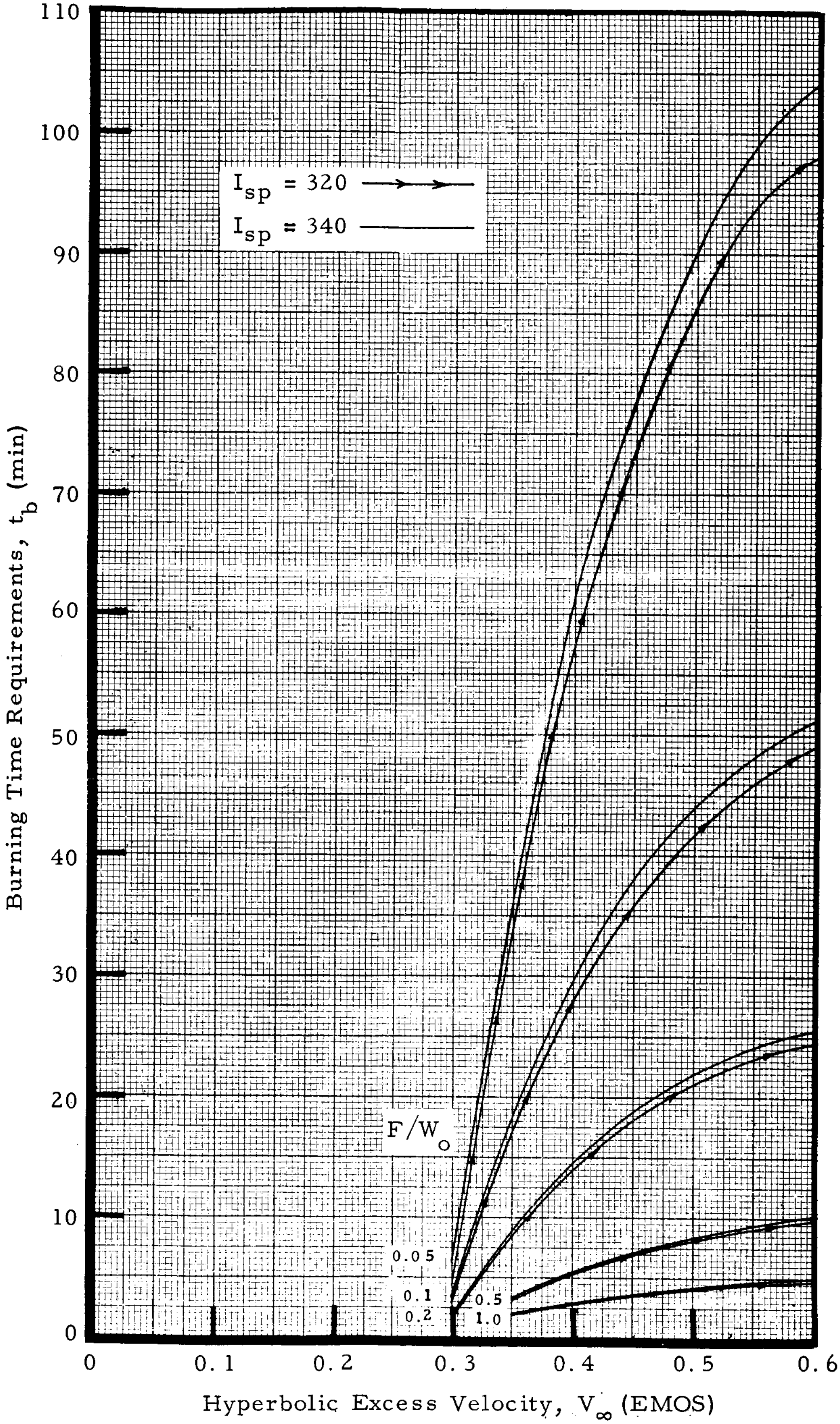


FIGURE 23c. BURNING TIME REQUIREMENTS FOR I_{sp} = 320 s AND 340 s, $(V_e)_{max}$ = 14000 m/s

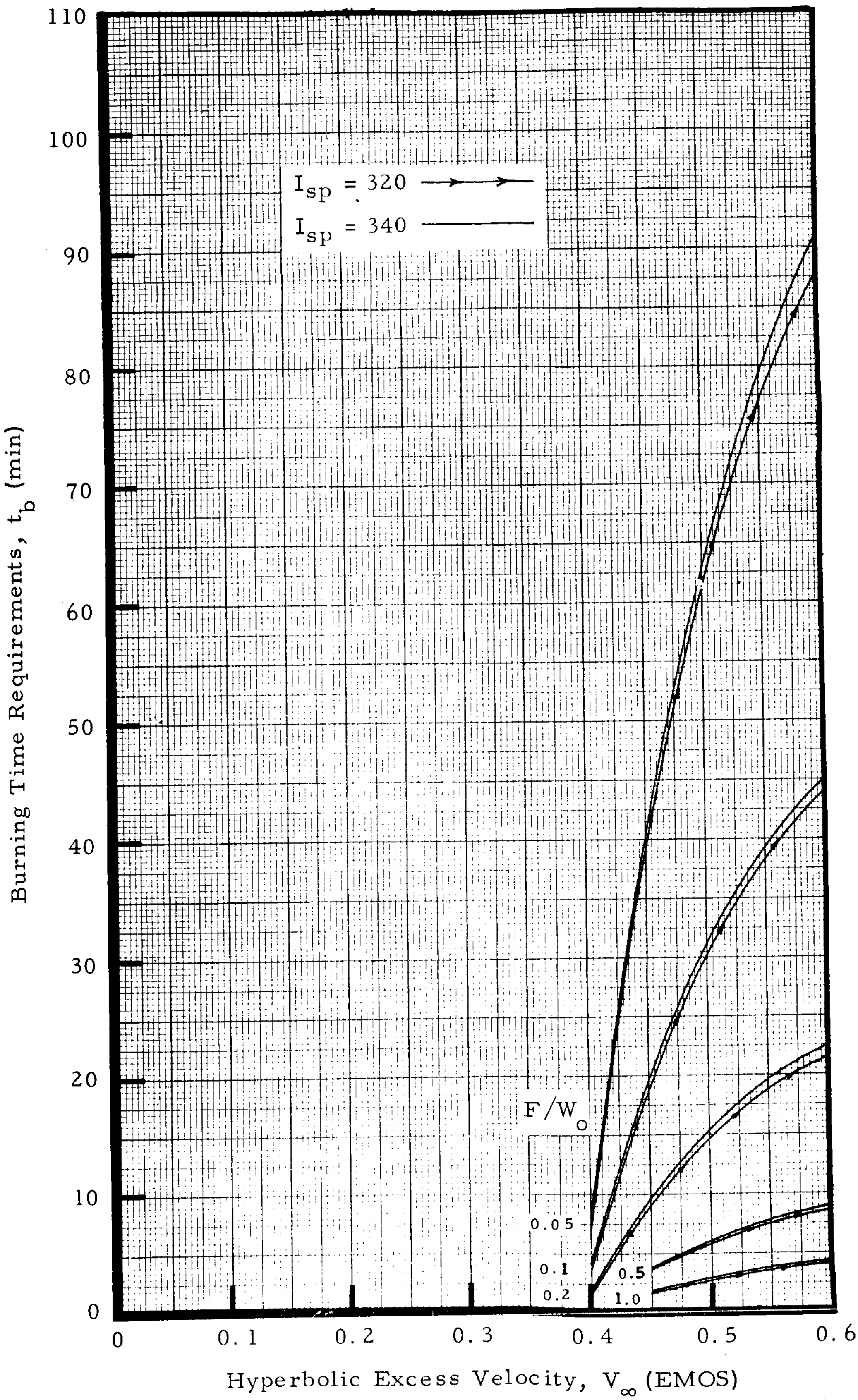


FIGURE 23d. BURNING TIME REQUIREMENTS FOR I_{sp} = 320 s AND 340 s, $(V_e)_{max}$ = 16000 m/s

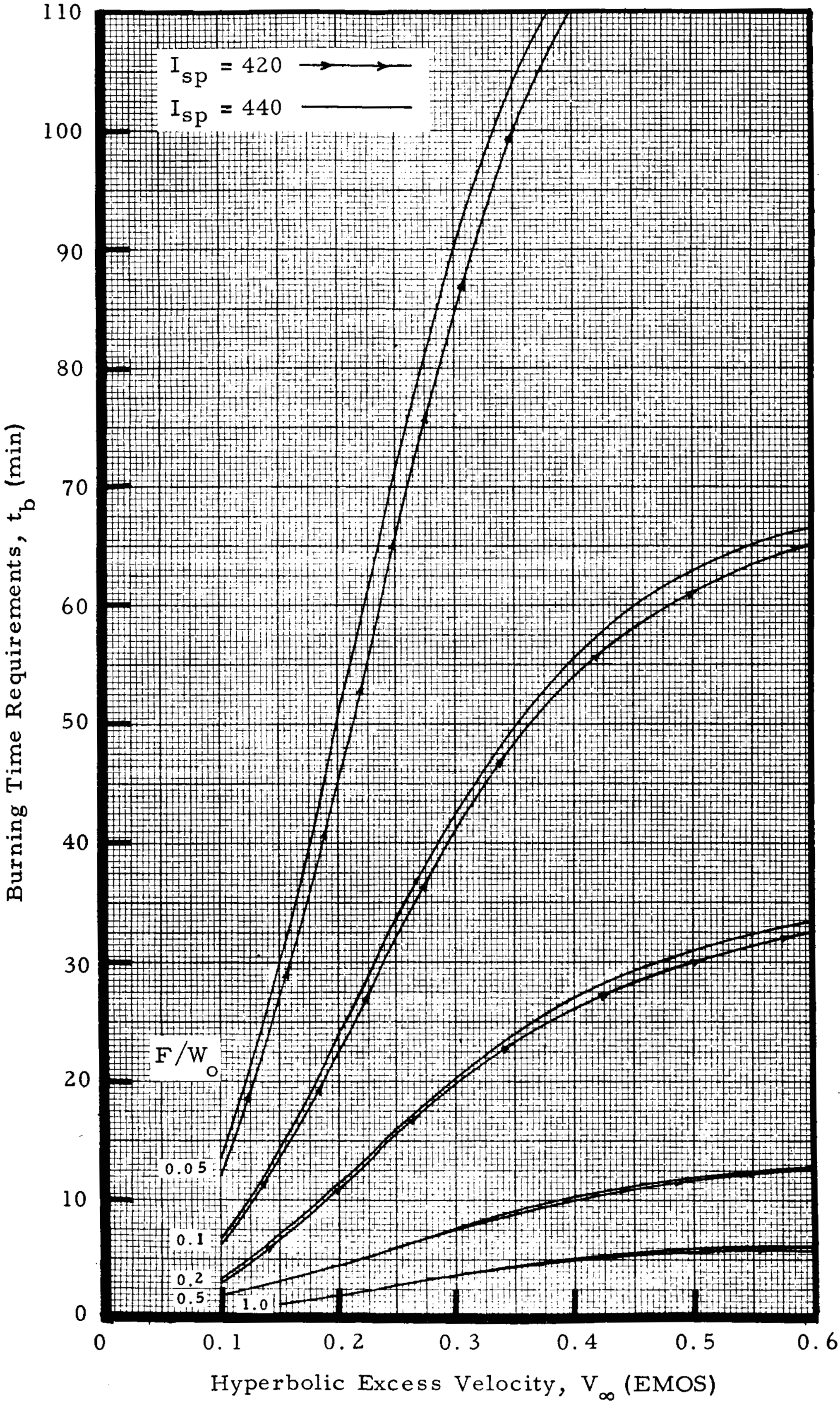


FIGURE 24a. BURNING TIME REQUIREMENTS FOR I_{sp} = 420 s AND 440 s, $(V_e)_{max}$ = 11030 m/s

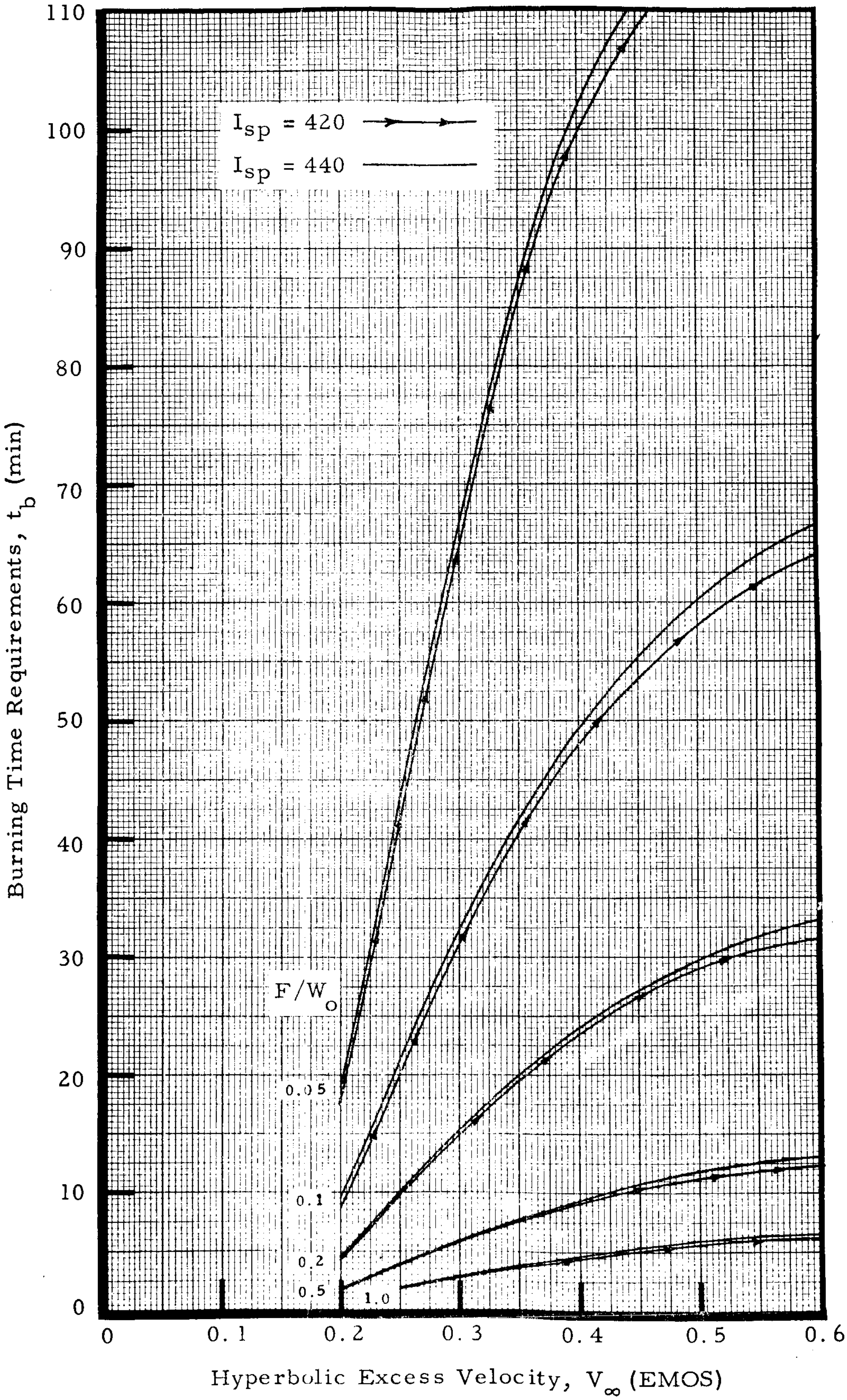


FIGURE 24b. BURNING TIME REQUIREMENTS FOR I_{sp} = 420 s AND 440 s, $(V_e)_{max}$ = 12000 m/s

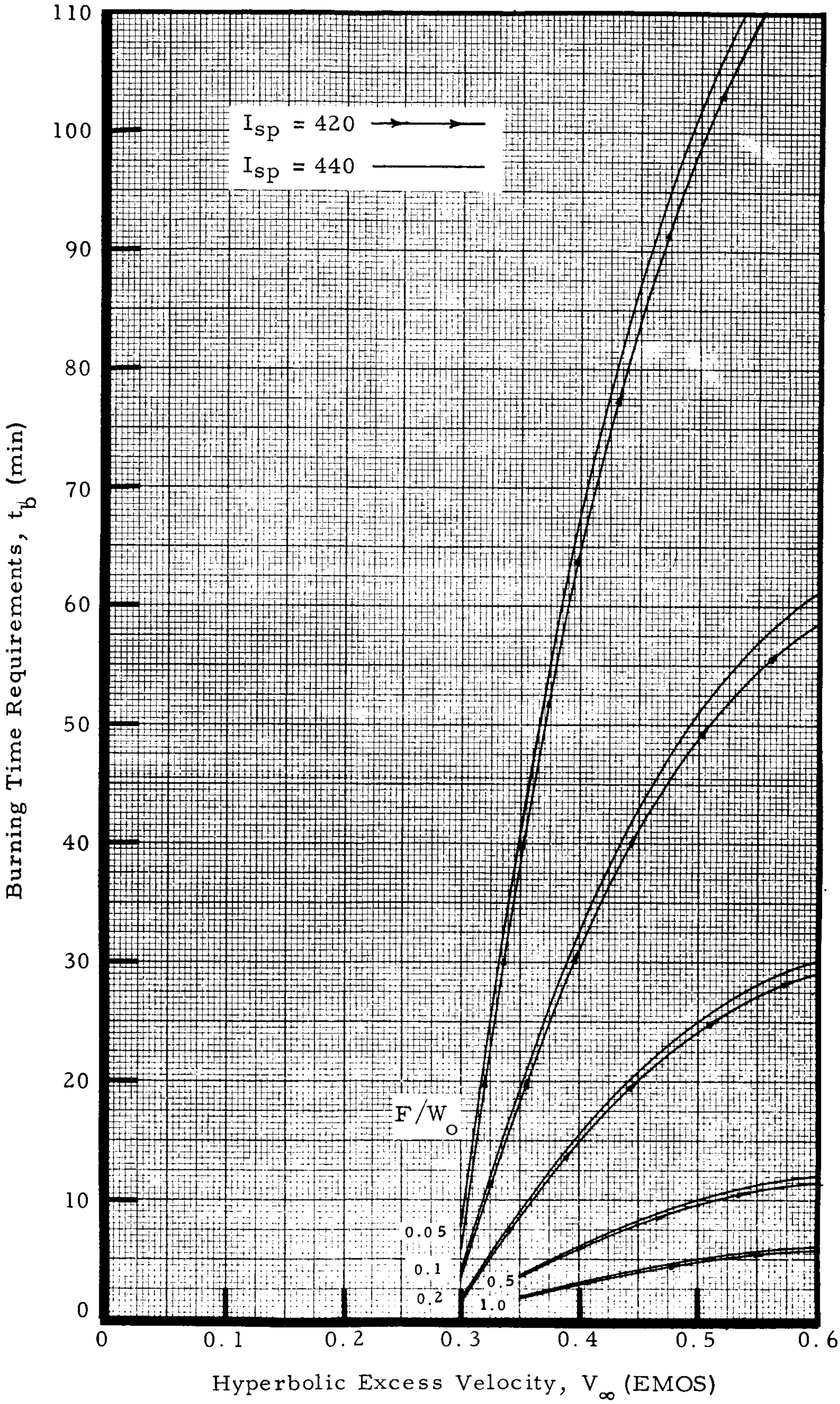


FIGURE 24c. BURNING TIME REQUIREMENTS FOR I_{sp} = 420 s AND 440 s, $(V_e)_{max}$ = 14000 m/s

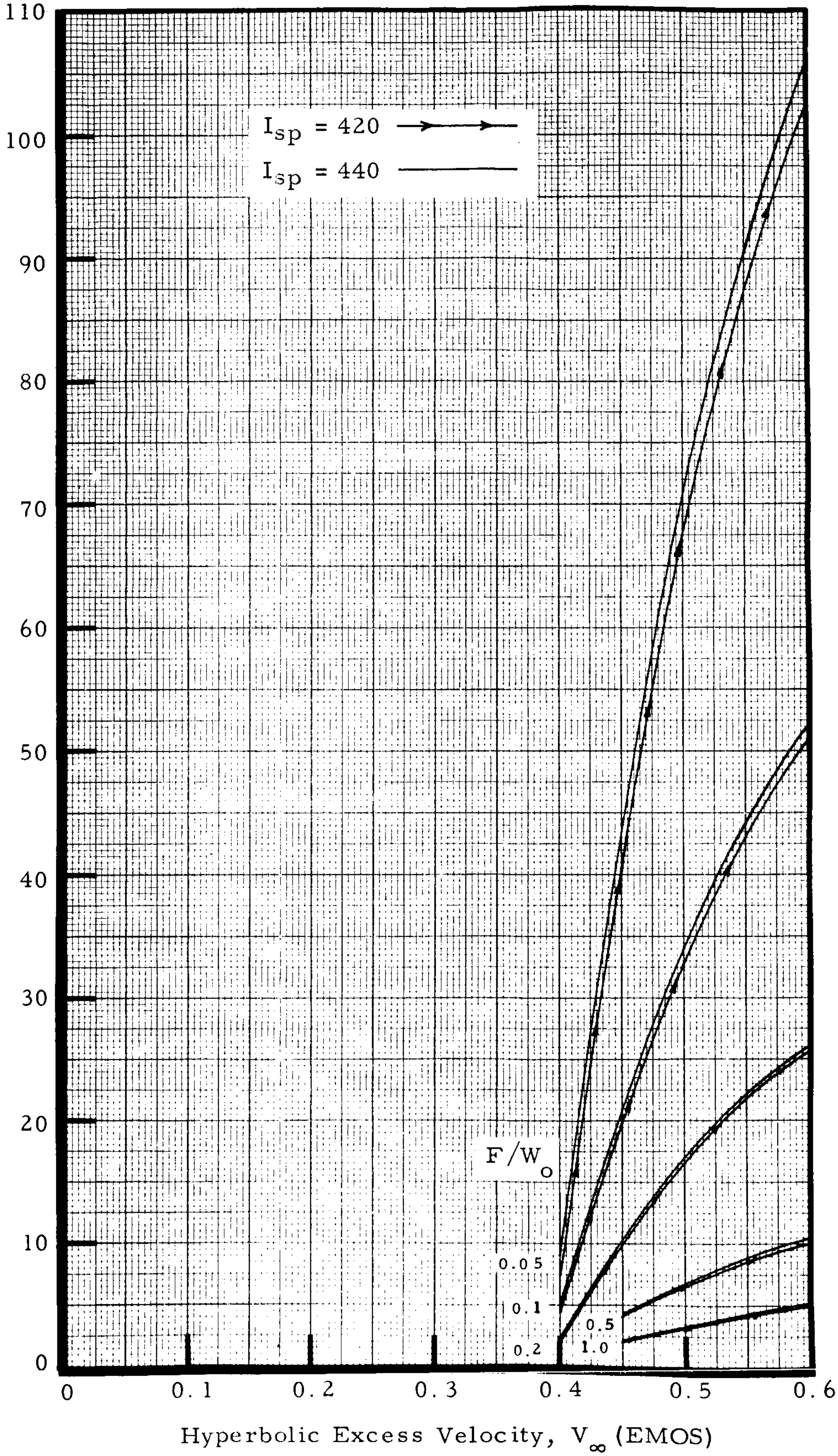


FIGURE 24d. BURNING TIME REQUIREMENTS FOR I_{sp} = 420 s AND 440 s, $(V_e)_{max}$ = 16000 m/s

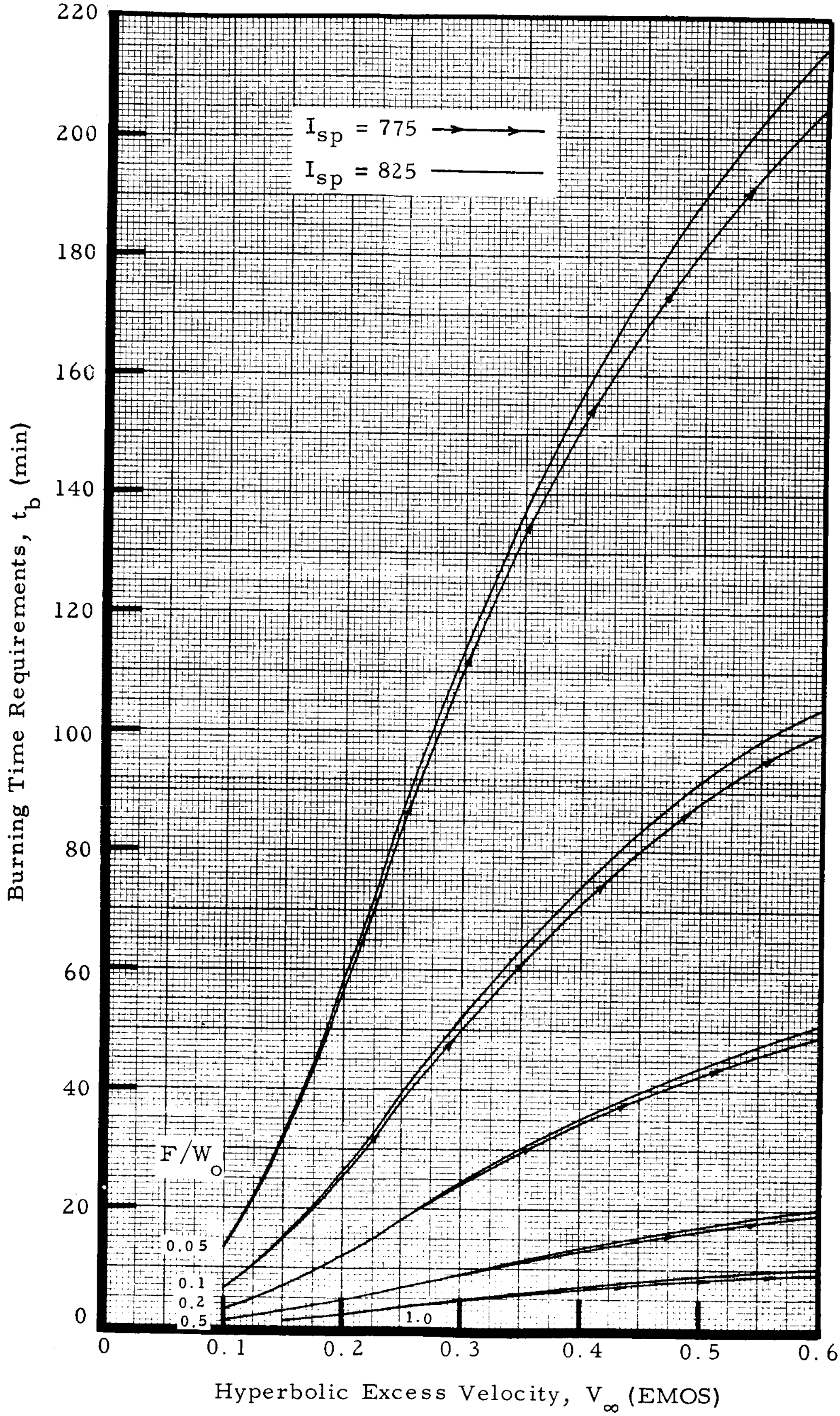


FIGURE 25a. BURNING TIME REQUIREMENTS FOR I_{sp} = 775 s AND 825 s, $(V_e)_{max}$ = 11030 m/s

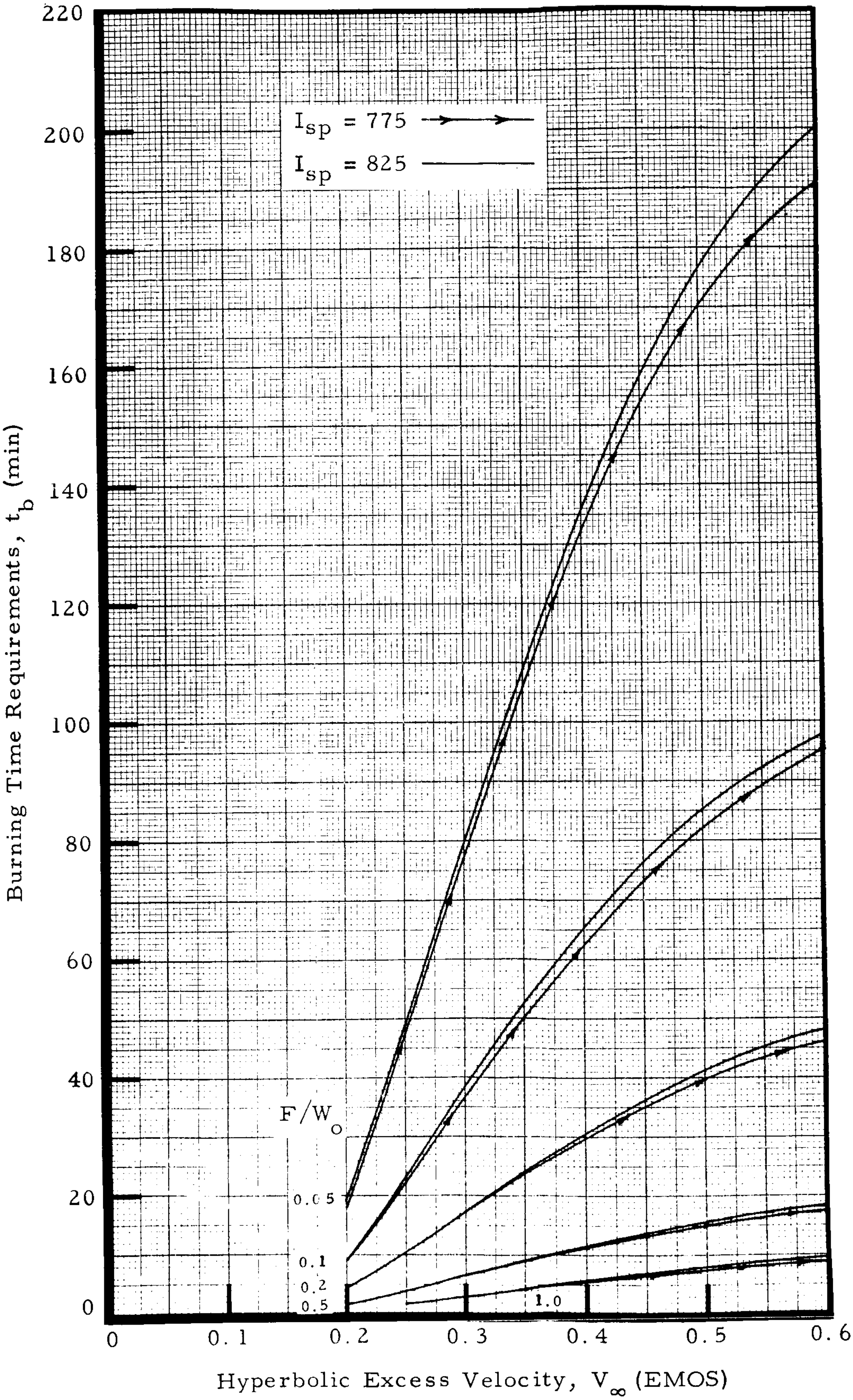


FIGURE 25b. BURNING TIME REQUIREMENTS FOR I_{sp} = 775 s AND 825 s, $(V_e)_{max}$ = 12000 m/s

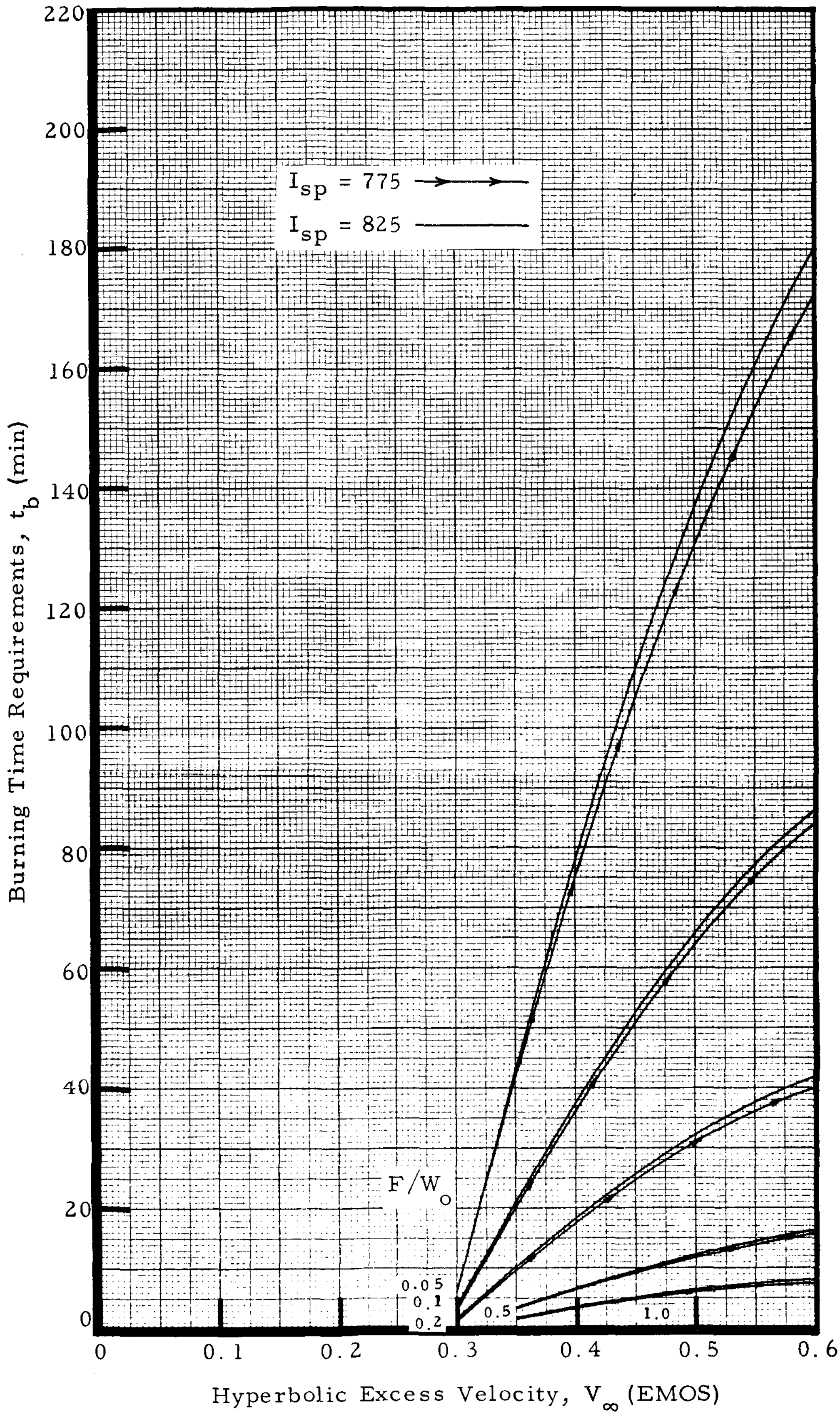


FIGURE 25c. BURNING TIME REQUIREMENTS FOR I_{sp} = 775 s AND 825 s, $(V_e)_{max}$ = 14000 m/s

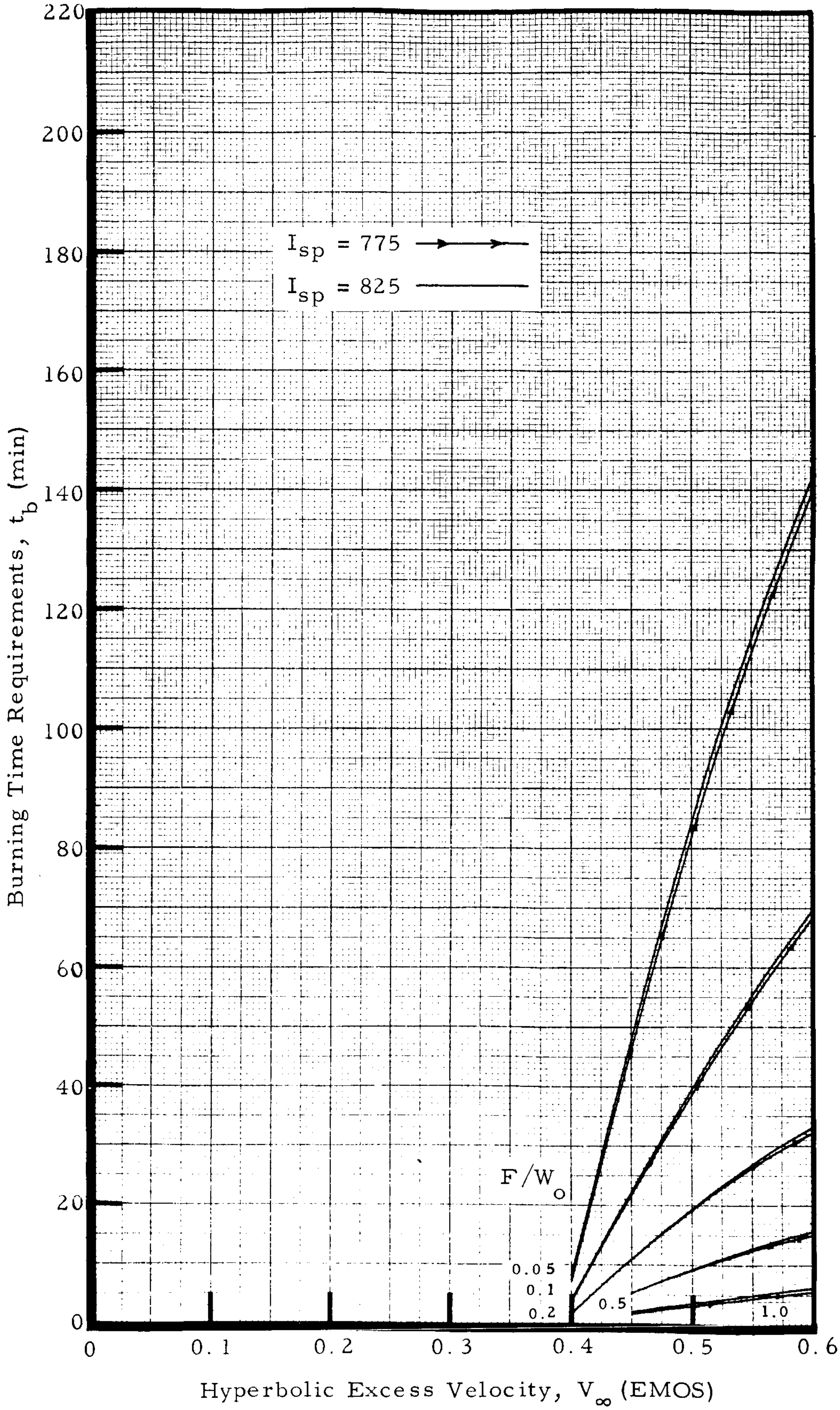


FIGURE 25d. BURNING TIME REQUIREMENTS FOR I_{sp} = 775 s AND 825 s, $(V_e)_{max}$ = 16000 m/s

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December 29, 1965 APPROVAL TM X-53375

VELOCITY REQUIREMENTS FOR THE EARTH RETURN PHASE OF PLANETARY MISSIONS

By

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The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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